Micro Gas Turbine Technology

Research and Development for European Collaboration

Technology Summary

ACKNOWLEDGMENTS

The Micro Gas Turbine Technology Summary has been produced by a technical Working Group composed by MGT OEMs, Heat Exchangers Manufacturers and R&D Institutes coordinated by the European Turbine Network (ETN). This document aims to identify a number of key areas that require substantial R&D efforts for micro gas turbines from the European community to become competitive in the energy sector worldwide.

Contributions to this document were provided by the organisations listed below:

Aurelia Turbines		ACTE		Ansaldo Energia	
Bladon Jets		Berlin Partner		Bosal	
Compower		DLR		Delta Motorsport	
DGTA		ENEA		Euro-K	
Fraunhofer		Hieta		HiFlux	
IRIS		INNECS		IMP PAN	
KTH		Mitis		MTT	
RSE		Price Induction		Samad Power	
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1 INTRODUCTION

The Micro Gas Turbine (MGT) Technology Summary has been produced by a technical Working Group composed by MGT OEMs, Heat Exchangers Manufacturers and R&D Institutes coordinated by the European Turbine Network (ETN). The Working Group aims to bring together MGT experts, to assess the development and market deployment of MGT technology.

The aim is to encourage through the preparation of a detailed summary, the investment for EU Industries and decision makers in further research and development for the MGT.

The first part of the paper provides an overview of the MGT and the challenges in developing the technology further in terms of system optimisation, material selection, reduction of production costs, reduction of maintenance and part replacement costs, life extension and hence reducing the environmental impact from system and part manufacturing. The document also analyses the results of international research projects.

The second part intends to give a full understanding of how the MGT integrated with CHP and RES could contribute in reaching the EU 2030 Climate and Energy targets.
The Expected Impact chapter aims to analyse the impacts of deploying MGT, focusing on the energy savings, the reduction of CO emissions and the higher flexibility to ease the integration of the RES into the power grid.

This summary concludes with a set of alternative research activities for the development of the MGT in the short and long terms.

Contents

2 VISION

The UNFCCC COP-21 has set forth the pace for the development of the next energy systems worldwide. Simultaneously EU countries have also agreed on the EU 2030 Climate and Energy package with the following targets:

- At least 40% GHG emissions reduction from 1990 levels by 2030;
- At least 27% energy efficiency increase by 2030;
- At least 27% renewable energy share by 2030;
- 15% increased energy interconnections between member states by 2030.

In this context, small scale power and heat generating technologies could play a crucial role to reduce the greenhouse gases emissions in the short and long term (by 80-95% by 2050 comparing to 1990 levels). Among the competing emerging technologies, Micro Gas Turbines (MGT) have the capability to help meeting the above mentioned energy targets with cost competitive, low emission characteristics, fuel efficient and fuel flexible operations. With these characteristics MGTs can support the increasing share of renewables and meet the challenges of the modern electricity grid.

Compact size, light weight, low maintenance, low noise, low emissions and multi-fuel capabilities make the MGT not only a transition technology for EU ambitious 2030 Energy targets but also a prime mover of the future for competitive, secure and sustainable micro-scale polygeneration.

The opportunities for MGT are numerous and in many areas, industries and environments: micro-CHP (Combined Heat & Power), portable power generation, marine auxiliary power and standby power, range extenders in hybrid vehicles, auxiliary power units in heavy vehicles and small unmanned air vehicles (UAVs). Given their high flexibility, the latest research and development activities have focused on hybrid MGT, which could be coupled for example with Concentrated Solar Power (CSP) dish and Solid Oxide Fuel Cells (SOFC). The advantages of such a hybrid systems could be easily seen in a further decarbonisation of the energy system, while assuring a security of the energy supply and back-up capabilities.

Though the MGT market is still considered a niche market, the recent development of MGT systems for households, could set up a new energy scenario in which industrial, commercial and residential customers produce power, heating and cooling in line with the decarbonisation of the energy system.

However to boost this technology at its full potential, with the support of EU institutions, significant investments and R&D activities need to be made and policies need to be defined in a way that promote a stable business climate which encourages low-carbon investments.

Europe can lead this technology development and transition with cooperation between industry and research institutes/universities supported by the EU.

2.1 MGT IN THE EU ENERGY SCENARIO

Due to the high share of renewables, the EU energy system is going towards decentralised power and heat generation. The role of the Utilities and independent power producers is changing as more rooftops deploy solar, more wind and hydro energy goes online and more micro-scale combined heat and power plants are put in place.

Among the challenges derived from a higher share of renewables, the intermittent generation characteristic of wind and solar energy sources is a main driver for the implementation of MGT systems. The MGT can provide fast and reliable power that is a need and a guarantee for grid stability.

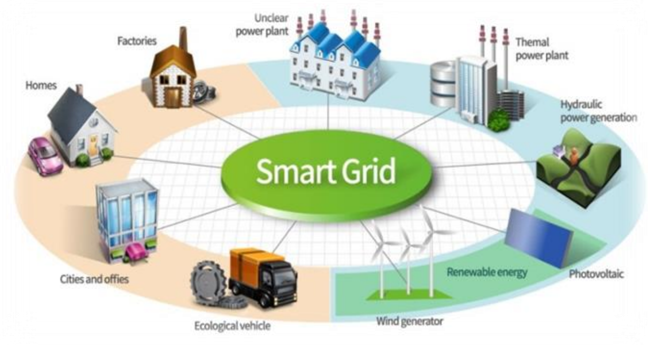


Figure 2-1: MGT in the Energy System

A decentralised power generation scenario integrating micro gas turbines along with wind turbines, photovoltaics systems, biomass plants, fuel cells and energy storage would provide a secure, stable, efficient, economical and environmentally friendly on-site energy production system, connected close to the consumers load and providing the end consumer with heat and electricity without major transportation and conversion losses. An important advantage of micro gas turbines to other heat engines for decentralised power generation is their capability to burn a variety of fuels, ranging from natural gas, diesel, LPG and hydrogen, to waste and biomass derived fuels like landfill gas or gasification products from biomass, which indeed is in the particular interest of this study. As a micro-scale fuel flexible system, MGT would be essential in the future energy scenario to guarantee security of supply and sustainable cost-efficient energy generation.

Given their Combined Heat and Power (CHP) configuration, also able to integrate RES, MGTs are technologies acknowledged by the European Parliament in its resolution on an EU Strategy on Heating and Cooling (2016/2058(INI)).
Adapting the current energy scenario into a truly sustainable one will require realizing the full potential for renewable energy sources to satisfy the heating and cooling demand. There will be equal efforts necessary from both generation and end-use sectors in order to achieve these ambitious targets for 2030.

In the short term, the MGT technology can absorb the fluctuations of the Renewable Energy Sources (RES) by using natural gas, hydrogen, biogas, industry waste gas, landfill gas, etc. In the long term, MGT applications can assure high utilisation of RES given their wider fuel flexibility and ensure security of energy supply by operating with natural gas or other gas when RES are not available.

In the first decade of the XXI century, MGT were proven to be reliable and working satisfactory, delivering over 30% electrical efficiency at full load, overall efficiency around 80% in CHP configuration, NO_x values below 15 ppm at 15% O_2 and availability over 90%

for a unit cost level of 800 €/kW [1]. For catalytic combustors levels of 3ppm NO_x have been reported but further developments are needed to extend the lifetime of the component.

The current challenging performance targets for micro gas turbines, in order to better fit into the EU energy scenario, include fuel-to-electricity efficiencies of 40% or higher, capital costs less than 500 €/kW, NO_x emissions reduced to single parts per million, between 1 and 2 years of operation between overhauls.

2.2 Integration with Renewable Energy Sources

In the future, energy supply has to rely especially on renewable energy sources. With increase deployment of intermittent, non-dispatchable renewables, a larger fluctuation in electricity supply is introduced. RES provide fluctuating and uncertain outputs and are bound to location-specific resources. This calls for back-up systems and hybrid technologies to secure and flatten the outputs. If EU is to lead the transition and meet its ambitious energy targets, a special focus in MGT technology is needed in order to develop its full fuel flexible potential and its ability to accommodate to other technologies under an integrated system.

2.2.1 Bioenergy

The use of biomass instead of fossil fuels has been considered for MGT since their entrance in the power generation market. The ability of MGT to operate with a wider range of fuels makes this technology already nowadays an attractive solution for biogas applications, agricultural and food waste, food processing, breweries, landfills, waste water treatment plants and human waste treatment. [2] Proven deployment of MGT in the biogas field is already a reality, with companies such as NewEnCo operating over 30 Turbec T100 units on untreated biogas fuel for more than 55,000 hours, overall efficiency of 80% and exceeding 94% availability [3].

Figure 2-2: Ansaldo Turbec T100 running with biogas

As bioenergy resources are location-specific and often scarce, fuel availability is also a market driver for MGT technology as there is a need of versatile energy conversion technologies in the micro scale (below 500 kW) in order to develop full potential of bioenergy sources. A particular attention has to be put on the economic scale of operation when designing a biomass CHP system. MGT technology which can use a broad range of fuels could overcome most of the current technical challenges and make the biomass systems more economically attractive. In fact increased fuel flexibility would ensure that cheaper fuels can be used when available, and that storage and conditioning can be minimized. The fuel mix can be also changed on varying market conditions. A large variety of suitable fuels makes the technology also usable in a wider geographic area. The decentralized application of the system supports the development of local biomass feedstock use, bringing also economic activities to the supply chain in rural areas.

In 2013 Biomass contributed to 15% of total EU primary energy production, with only 3% of solid biomass imported from outside the EU, indicating that it is mainly a local fuel. Biomass supplied 14,7% of EU heat and 7,5% of electricity in the EU [4]. Many countries, especially in eastern and northern EU are depending on biomass in their National Renewable Energy Action Plans for their 2020 goals. CHP using a wide range of biofuels is one of the priorities of H2020 Programme, and is identified by the European Strategic Energy Technology Plan (SET-Plan) for its potential in contributing to meeting the goals of 2020 and 2030 CO_2 reductions and beyond, as well as the target for an increase in renewable energy generation and its increased use in applications such as heating and power.

Though biomass power generation technologies are more expensive and there are still some technological barriers to overcome, MGT can handle both liquid and gaseous fuels with variable compositions [5], as opposed to other competitive technologies, and their use would allow a reduction of the greenhouse gas (GHG) emissions and lower costs of energy. At the same time using indigenous feedstocks increases the self-sufficiency of the EU energy system. Biomass CHP could also be used to balance the intermittency of other renewables and the varying heat/power ratio can be used to combat seasonal differences in heat and electricity demand.

According to the type of feedstock available, MGT can burn biomass with an internal and/or external combustor. Direct combustion of biogas in the MGT for CHP is a mature and commercially available technology. The externally fired MGT has two main advantages. On the one hand, the utilisation of the waste heat from the turbine in a recuperative process and, on the other, the possibility to operate with direct combustion of exotic fuel.

2.2.2 Concentrated Solar Power

Concentrated Solar Power (CSP) is a technology that converges a large area of sunlight into a smaller area. That heat source can be used subsequently to generate electricity.
CSP from solar dish configurations can provide high levels of temperature to the working fluid, between 800-1000°C. In these levels, MGT technology allows efficient integration of CSP and provides a reliable, long-life, low noise and reduced maintenance power generation system.
This system could operate both in a stand-alone configuration providing eco-friendly electricity in remote locations or connected to the grid, or in farm arrangement to provide higher outputs.

Figure 2-3: CSP dishes in farm arrangement

Currently, the Stirling engine is the selected technology for micro-scale solar dish CSP. However they suffer from a number of technical problems affecting life and reliability, such as issues with cylinder seals, hot spots in the heater and difficulties with part-load control. Such problems lead to system complexity and increased costs. Internal Combustion Engines (ICEs) are not a suitable contender for concentrated solar power applications because of their basic engine cycle and design principles. MGT with CSP could be a potential alternative technology in this field.

Figure 2-5: BiostirlingSka system

Figure 2-4: OMSoP system

The main components for a MGT-based CSP system are the dish concentrator, the receiver unit and the MGT. All three components are independently available today either commercially or in conceptual form, but they have not been developed to operate together in the target power range. Currently, the integrated system is being demonstrated at large scale for a 3-10 kWe system with the OMSoP project, funded by EU under the H2020 Working Programme.

In current years, there is an increased interest in developing technologies that can handle renewable energy sources and provide as well dispatchable power. One of the objectives of the OMSoP project is to demonstrate that MGT technology can be hybridized to handle both solar heat input and natural gas to provide dispatchable, continuous, reliable and stable power with a high share of solar power when available. This characteristic makes MGT distinguishably competitive against photovoltaics technology. Future research activities could focus on the integration of the system with storage technologies and/or an absorption chiller for polygeneration.

2.2.3 Fuel Cells

The concept of hybridising the MGT with fuel cell has been developed since the MGTs started to be applied for the power generation sector, though the commercialisation of such a system was never done given the high costs of the technology and the novelty of the fuel cells.

There are different types of fuel cells that can be hybridised on with MGTs, however the hybridisation with SOFC seems to be the most suitable, as this works at temperatures of about 950˚C, which is high enough to be used for the operation of a micro gas turbine. Furthermore the exhaust gases of the turbine can be utilised for the preheating of the fuel cell. Considering that the fuel utilisation of SOFC is about 80% to 85% [6], it is possible to burn the exhaust gas of the fuel cells in the combustion chamber of the turbine.

The world's first hybrid MGT/SOFC system, with a power output of 220 kW (200 kW from the SOFC and 20 kW from the MGT) was installed in 2005 at the University of California. The system has demonstrated an electrical efficiency of 53%.

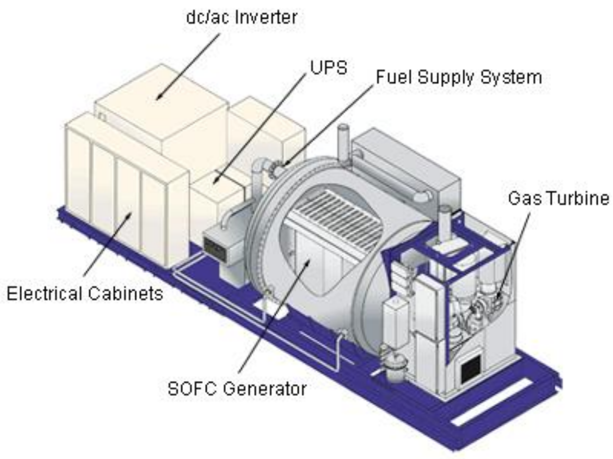


Figure 2-6: Hybrid System SOFC/MGT (220kW)

However the size of the fuel cell, the high cost of the system and the low demand on the market for decentralised power generation system didn't push the development of this technology forward. Nowadays the shift towards a decentralised power generation market, the increase of fuel cell output and the decrease of its volume, coupled with the increased of MGT efficiency and capability to handle different type of biofuels, makes this system a promising technology for distributed power supply.

The integration of MGT and SOFC may be direct or indirect. In the indirect configuration, the coupling of the two components would be done via a heat exchanger, which would present issues related to temperature limitation. With direct integration, the exhaust of the fuel cell would directly heat up the air from the MGT compressor. Additional fuel injection would allow an optimisation of the efficiency gain. For this last configuration the potential efficiency is about 73%.

Nowadays research activities for the integration of these two technologies are still going on. The European Commission has funded the BioHypp (Biogas-fired Combined Hybrid Heat and Power Plant) project within the Horizon 2020 Work Programme. The main objective of this project is to develop and realise a full-scale technology demonstrator of a hybrid power plant in a lab environment suitable for gaseous sustainable biomass feedstock derived from fermentation processes. Realising this system will validate the great potential of the hybrid plant concept as an efficient and energy-sustainable source of heat and electrical power. The project, started in June 2015, will run for 4 years.

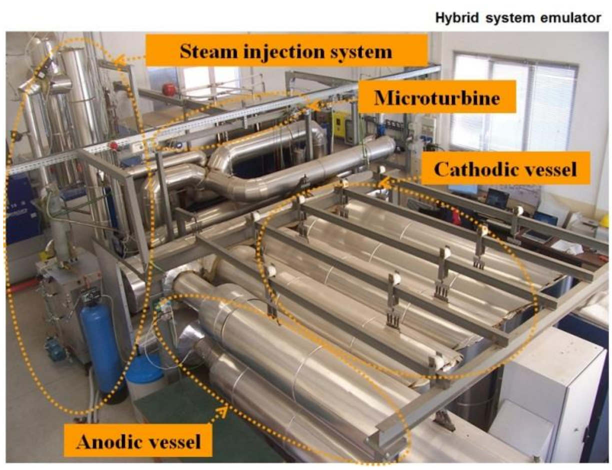


Figure 2-7: Hybrid system emulator of the BioHypp

3 MGT TECHNOLOGY

3.1 DEFINITION

MGT stands for Micro Gas Turbine. These are complex systems, developed on the Ericsson cycle, used for micro-scale power generation at one point in a distributed network or at a remote location. These devices can be used in stationary, transport or auxiliary power applications.

The European Turbine Network (ETN) refers to a system-based definition for micro gas turbines, whereby MGT are small gas turbines combined with a high speed generator. The authors recognise that this definition does not define the output range; however, the technological requirement of a high speed generator for gas turbines is inherent of the micro/small scale. In this regard, these systems do not typically exceed 500 kWe.

In the literature, the prefix "micro" can refer to different output ranges depending on the source, and therefore the actual boundary between micro, small and large gas turbine is vague. Some authors refer to micro scale systems as units with power outputs between 3 to 250 kW or 300 kW while other reports label MGT as any gas turbine below 1 MW. The European Union, on the other hand, defines a micro-cogeneration unit based on the electrical power output with a maximum capacity below 50kWe. Their boundary for small-scale units is set to a maximum of 1MWe. Not only the ranges are different but in addition, the types of output (shaft, electrical or thermal output) are different or not mentioned in many cases.

A MGT typically includes the following components: compressor, turbine, combustor, bearings, recuperator, high speed generator, power conditioning and control unit, enclosure and balance-of-plant [7]. Some of these components might not exist in a particular MGT and depend on the application and requirements of the system.

Micro gas turbine main characteristics[1] are:

- Electrical Output: 3 to 500 kWe
- Thermal Output: 3 to 1,500 kWth and exhaust gas temperature between 250-300 ºC
- Fuel flexibility: Natural gas, hydrogen, sour gas, gasoline, kerosene, diesel fuels, heating oil
- Electrical efficiency range: 23-40%
- Total efficiency (CHP) range: 80-90%
- Reliability and life: 40,000 to 80,000 hours with overhaul
- Emissions: below 3 ppmv for NOx on fossil fuels. Noise levels below 50 dBA
- Modularity: Ability to group units in farm arrangement and share equipment and infrastructures.
- Low weight: 23-30 kg/kW
- Compact system: 0.045-0.065 m^3/kWe
- Low maintenance: Typically single radial stage and single rotating part
- Air cooled

[1] Average data given by the OEMs drafting this summary.

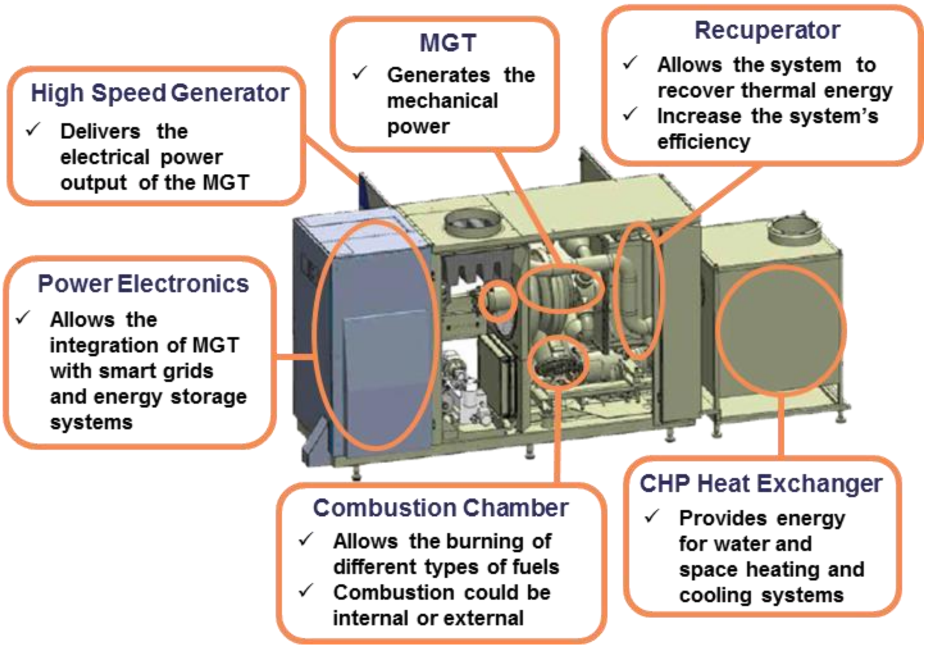


Figure 3-1: Ansaldo Energia T100 MGT system for CHP applications

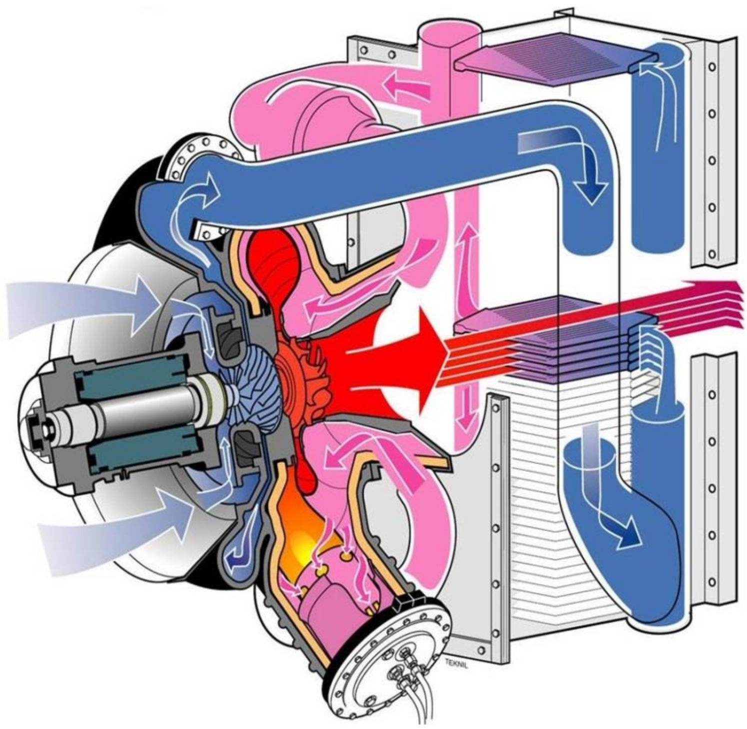


Figure 3-2: Sectional drawing Ansaldo Energia T100

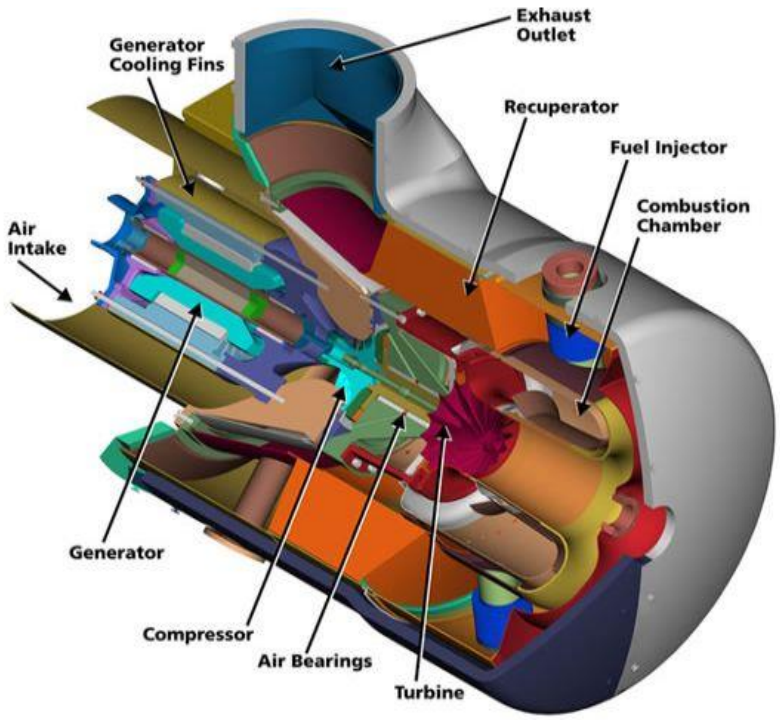


Figure 3-3: Capstone C30 sectional drawing

With regards to the MGT costs, it must be noted that the power range and the volumes affect the cost distribution. For power range between 1 – 10 kW, the below table shows the production cost for the single components

The cost of the various components or subsystems ranges from:

- compressor and turbine 13-15 %
- combustor 8-11%
- bearings 3-4 %
- recuperator 21-24 %
- high speed generator 9-11 %
- power conditioning and control unit 22-24 %
- enclosure and balance-of-plant 17-20%

For power range between 100-300kW, the split of the cost is the following:

- compressor and turbine 25%
- combustor 8%
- bearings 1%
- recuperator 25%
- high speed generator 5%
- power conditioning and control unit 25%
- enclosure and balance-of-plant 11%

3.2 APPLICATIONS

Relative to other technologies for small-scale power generation, micro gas turbines offer a number of advantages, including: a small number of moving parts, compact size, light weight, low emissions, low electricity costs, reliable operations, potential for low cost mass production, and opportunities to utilize waste fuels and energy recovery. They have been commonly used in many engineering fields and have already been proven to be reliable and working satisfactory [1], suitable for integration with other systems or as a subsystem in a larger energy system.

Micro gas turbine market focuses on different commercial sectors where there would be a need for cost-effective electrical and thermal power such as hotels, schools, hospitals, retail shops and office buildings. MGTs are also an attractive system for remote and reliable electrical power generation for telecommunication, mining, humanitarian missions or military applications.

MGTs also operates in resource recovery operations at oil and gas production fields, wellheads, coal mines and landfill operations using the by-product gases as fuel. The system can therefore provide thermal oxidation of very low Btu fuel such as landfill or waste gases and generate effective electrical output.

Although variable due to market trends and economic climate, oil and gas applications represent typically 50% of the MGT market for the largest manufacturer Capstone, 40% represents commercial and industrial CHP, 8-9% is applied in renewable energy applications and the last 1-2% covers other markets such as hybrid vehicles or marine applications [2].

3.2.1 Energy

Power generation

For ground based power generation, there is competition from many alternative technologies such as small piston engines, fuels cells and Stirling engines. These are all focused on energy saving and often in cogeneration configurations. Especially for the very small scales MGTs (below 100 kW), electrical efficiency is often lower than most alternative prime movers and competitiveness is maintained using the specific benefits of the gas turbine including fuel flexibility, power density, low emissions, low noise.

Remote Power

Micro gas turbines can provide electrical power for remote applications where the access to the power grid would be too costly or inexistent such as rural, desert or marine environments. They can then operate as a stand-alone unit in off-grid operations or grouped in farm arrangement generating higher output

Figure 3-4: SCADA Metering station for Oil & Gas operations

and providing electrical power support to a local microgrid. Micro gas turbines offer flexibility in operations, fuels and connection methods, modularity, stable and reliable operations and lower emissions than alternative generation systems, making them suitable for the Oil and gas sector off-shore and on-shore.

Energy Savings

MGTs can also be connected to the grid to perform peak shaving. This is especially attractive for commercial applications. When the power usage peaks, the MGT operator can reduce electricity costs by generating the additional load in a short time. The inherent characteristics of this technology (compact size and low gaseous and noise emissions levels) allows the system to operate where other power generation units would not be capable.

Critical Power

Additionally, micro gas turbines are used as back-up power or as part of uninterruptible power supply systems. They allow a continued and quality electrical supply to power-sensitive commercial applications such as data centres, hospitals or telecommunications. The application of micro gas turbines as back-up power generation is attractive for any business where power shut-downs results in sensitive loss of revenue or damage to assets.

Polygeneration

Micro gas turbines used in co-generative applications have proven to be a promising technical solution for high efficiency energy conversion. These comprise both Combined Heat and Power (CHP) and Combined Cooling/Heating and Power (CCHP). The exhaust gas temperature of micro gas turbines, commonly around 300ºC, can be used directly for heating and industrial processes or be recovered in a heat recovery boiler (CHP) or an absorption chiller (CCHP). Cogeneration MGT units have been installed in commercial environments such as hotels, schools, hospitals or retail shops and industrial locations for small operations needing hot water or low pressure steam for wash water such as the food and manufacturing sectors. The use of the exhaust gas temperature allows MGTs to significantly increase their overall efficiency up to 90% and be an attractive solution for applications that require their range of electrical to thermal output ratio.

For example, Turbec T100 CHP units have been installed in 2016 at the Leafy Resort Wellness Spa in Gargnano, Italy. The units provide an electrical availability of 200 kWe and a thermal availability of 300 kWth, equipped with an absorption chiller, a biomass boiler and a high-efficiency natural gas boiler.

Figure 3-5: Turbec T100 units at Leafy Resort Wellness Spa for CCHP

3.2.2 Transportation

Range Extender

Electric vehicles biggest challenges are their limitation in battery capacity, where Li-ion batteries are two orders of magnitude lower in specific energy (MJ/kg) than conventional gasoline fuel. This significantly reduces the electric vehicles range and implies a larger number of stops for recharging the batteries. A solution to this problem is the use of micro gas turbines to recharge the batteries when these are close to being empty. The micro gas turbine can operate at optimum load, providing an efficient and low emission on-board recharging system for the electric vehicle. This is especially applicable to transit buses and heavy-duty trucks.

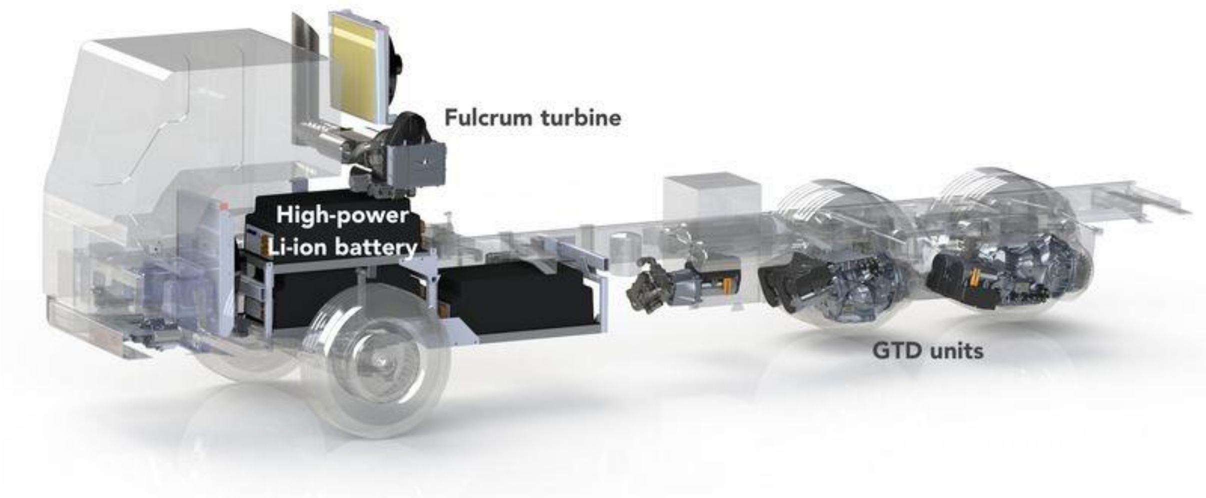


Figure 3-6: Tandem drive truck with Route powertrain using Fulcrum turbine (80kW)

UAV/small aircraft propulsion

For aircraft and Unmanned Aerial Vehicle (UAV) propulsion there is a rapidly growing demand for small scale light and efficient propulsion systems. The leading market here is military which means information on development projects is mostly classified. However, also the civil UAV market is growing rapidly and may well eventually inherit technology from the military projects. Currently, the micro gas turbine development resources may well be largest in the military sector. Therefore, also future ground based MGT technology may well come from the aircraft UAV engine, similar to the current aero-derivative industrial gas turbines. It is clear that for UAV operational requirements such as range and endurance, improving engine efficiency is key (except for some very specific application such as missiles).

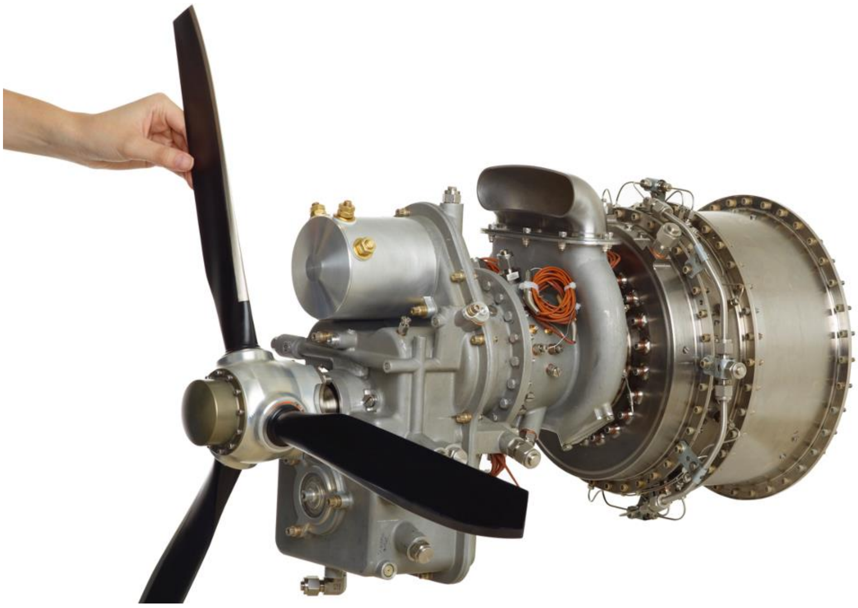


Figure 3-7: UAV Turbines

3.3 TECHNOLOGY BACKGROUND

The development of the MGT started in the late 80ies. Important driver was the automotive industry which for many years had been active in development of small gas turbines with mechanical drive as an alternative for diesel and gasoline engines (internal combustion engines – ICE). Main reasons are the advantages of the gas turbine regarding low emissions, fuel flexibility and a potential to compete on cost with ICE. Connected to a high speed generator instead of mechanical drive the technology became very suitable of use in hybrid vehicles. However at that time (1990ies) the hybrid electrical drive train was not a technology that was mature enough for the market.

Instead other non-automotive companies picked up the MGT technology and introduced it on the decentralized power generation market where its long life and low maintenance cost could compensate for higher first cost. Decentralised power generation is now a fast growing market.

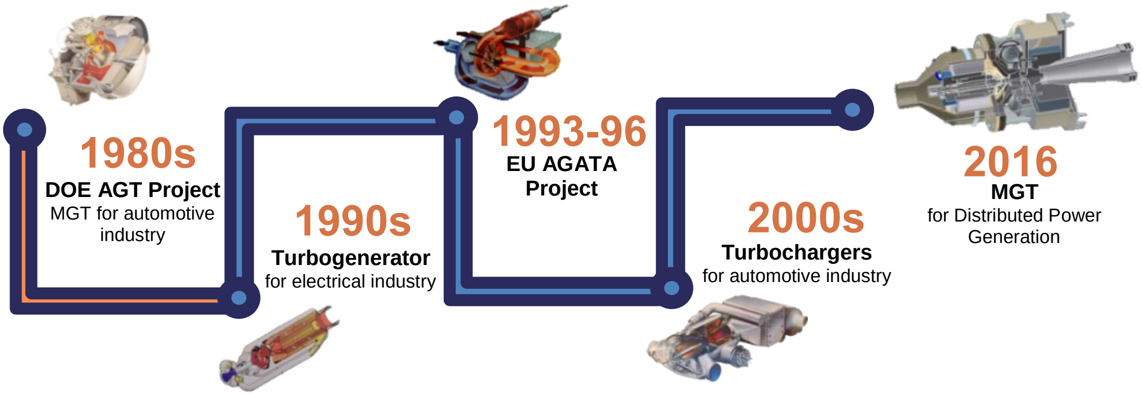


Figure 3-8: MGT Technology development

3.4 Technology Description

Micro gas turbines operate on the Brayton Cycle. This is the simplest form of a gas turbine cycle: air at atmospheric conditions is compressed, fuel is added and burned at constant pressure and then the compressed and heated air is expanded through the turbine back to atmospheric pressure. The recuperated form of this cycle allows to save fuel by recuperating the extra heat from the exhaust gases and exchanging it with the cool air after the compressor by means of a recuperator.
However, micro gas turbines differ from larger gas turbine in several operating and system characteristics.

First of all, micro gas turbines are significantly smaller in size and output than large gas turbine, hence their name. Large gas turbine typically measure around 10x3x3 m^3 and electrical outputs ranging from 2 to 500 MW whereas micro gas turbine dimensions are around 3x1x2 m^3 and power outputs below 1 MW.

Micro gas turbines operate at significantly higher revolutions. With smaller size, typical problems such as tip supersonic speeds or mechanical limits are delayed to higher rotational speeds. Therefore micro gas turbine can operate up to 140,000 rpm whereas larger gas turbine will typically operate in the range of 3,000 to 20,000 rpm.

Additionally, because of their reduced size, micro gas turbines typically operate a single radial compressor stage delivering a pressure ratio between 2 and 5. These provide reasonable stage efficiency and a more compact design. Larger gas turbines would operate several axial compressor stages, allowing generating high pressure ratios up to 25.

Combustion temperatures are also reduced for micro gas turbine, ranging between 900 to 1000 ºC whereas larger gas turbines reach turbine inlet temperatures of 1500 ºC. This is mainly due to the reason that cooling micro gas turbines is expensive and difficult.

Micro gas turbines are, as expected, less efficient than larger industrial gas turbines, where the larger dimensions allow overcoming technical inefficiencies. Therefore, in order to increase the overall efficiency of micro gas turbines, operating at lower pressure ratio and temperatures, these units include a recuperator after the turbine. The recuperator allows recovering part of the waste heat and delivering it at the turbine entry and therefore increasing the system efficiency.

However, the compact size and simple design allows for significant benefits such as easy installation, modularity, use of air bearings, low maintenance, simple operations and low NO_X emissions (connected with low pressure ratio and temperature).

Several competing manufacturers are developing units in the 25-250kWe range. Multiple units can be integrated to produce higher electrical output while providing additional reliability should one need repair or maintenance. Most manufacturers are pursuing a design where the compressor, turbine and generator are mounted on a single shaft supported on lubrication-free air bearings and operating at speeds of up to 120,000rpm.

A schematic diagram of the ANSALDO AEN-T100 is illustrated below:

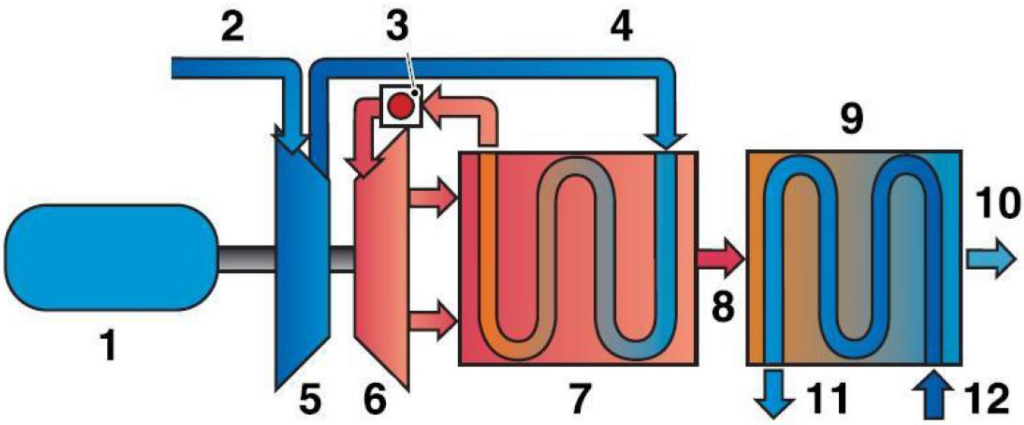


Figure 3-9: Schematic diagram Ansaldo AEN-T100 with CHP

1.	**Generator**	**7.**	**Recuperator**
2.	**Inlet air**	**8.**	**Exhaust gases**
3.	**Combustor chamber**	**9.**	**Exhaust gas exchanger (PH vers.)**
4.	**Air to recuperator**	**10.**	**Exhaust gas outlet**
5.	**Compressor**	**11.**	**Hot water outlet(PH vers.)**
6.	**Turbine**	**12.**	**Water inlet(PH vers.)**

Typical operating conditions for the AEN-T100 are:

- Combustion chamber pressure = 4.5 bar
- Turbine Inlet Temperature = 950°C
- Turbine exit gas temperature = 620-650°C
- Exhaust gases temperature = 80°C
- Rotation speed = 70000 rpm
- Electrical efficiency = 30±2%
- Total efficiency (CHP) = 80%

Compressor and Turbine

Micro gas turbine compressor and turbine are typically single stage radial designs that allow for a compact design and higher efficiency in small scale. Axial stages are commonly more efficient than radial stages; however this is not the case for small scale as the blade height for axial stages would be impractical.

Additionally, MGT compressor, shaft and turbine are manufactured as a single part which significantly eases maintenance activities. They commonly operate on oil-lubricated or air bearings. Oil-lubricated bearings is a proven and developed technology, however it requires all the associated systems for oil (pump, filter and cooling) and therefore increase design, manufacturing and maintenance costs. Air bearing systems are simpler in design and maintenance, making them a very attractive solution for micro gas turbines.

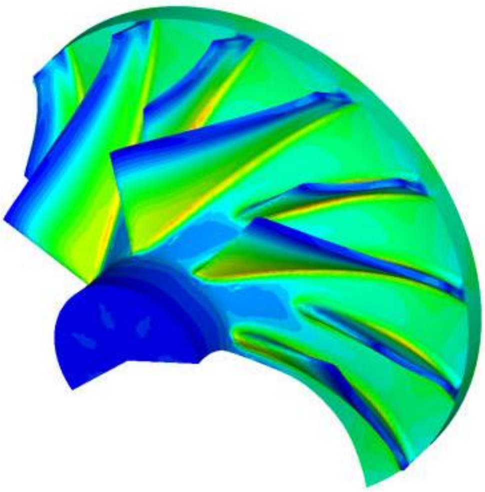


Figure 3-11: MGT compressor

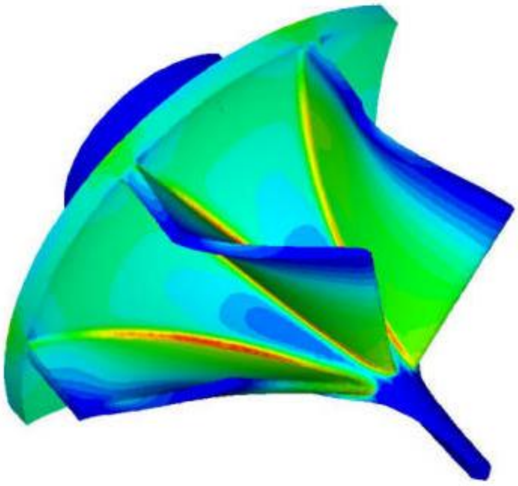


Figure 3-10: MGT Turbine

Combustion Chamber

The combustion chamber is the part of the engine where air is mixed with fuel and burned with high pressure air coming from the compressor. The hot gases generated pass through the turbine's section, where the thermal energy is converted in mechanical energy. Despite very high air flow rates a combustor must contain and maintain stable combustion. To do so combustors are carefully designed to first mix and ignite the air and fuel, and then mix in more air to complete the combustion process. In MGT combustion may be direct (internal firing) or indirect (external firing).

Combustion chambers help in operating characteristics, such as levels of emissions, fuel efficiency, and transient response (the response to changing conditions such a fuel flow and air speed).

Recuperator

The recuperator is essentially a heat exchanger between the hot exhaust gas leaving the turbine and the cooled air leaving the compressor. Air leaves the compressor at a typical temperature of about 150-200ºC and exchanges heat with the exhaust gases at 600-700ºC. This allows increasing the temperature of the working fluid at the entry of the combustor and therefore reducing the fuel needed to reach turbine inlet temperature. This fuel savings translate in almost double the original efficiency of the micro gas turbine. Nonetheless, the use of a recuperator is also associated with a higher pressure drop that ultimately translates in a reduced power output.

Figure 3-12: HiETA Technologies - MGT Recuperator

Electric Generator

The electric generator is part of the overall gas turbine package and responsible of delivering the electrical output power of the micro gas turbine system. It is typically coupled directly to the high-speed compressor-turbine shaft or through a gearbox at conventional 3,000 rpm.

High-speed generators imply the reconversion of high frequency AC electrical power to 50Hz or 60Hz outputs. This process is associated with an efficiency penalty of 5-10% due to the rectifying and inverting of the signal. However for some single shaft machine designs, either a standard induction or synchronous generator can be used without any power conditioning electronics needed.
At start-up, the electric generator operates as an engine to run the micro gas turbine.

CHP or CCHP Heat exchanger

If the micro gas turbine operates as a CHP or CCHP unit, the system includes a second heat exchanger that uses the remaining exhaust thermal energy after the recuperator. The available exhaust gas, typically at 300ºC, provides energy for water and space heating, cooling systems such as absorption chillers and for process heat applications.

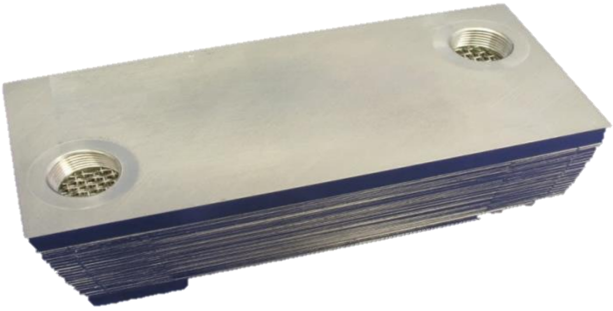


Figure 3-13: Mitis Heat Exchanger

3.5 COMPARISON WITH OTHER TECHNOLOGIES

For both ground based power generation and micro CHP applications, there is competition from several alternative technologies. These technologies are briefly described below.

Internal Combustion Engines

Stirling Engines

Rankine Cycle Turbines

Pico Turbines

Fuel Cells

Internal Combustion Engines

In the ICE the combustion of a fuel occurs with an oxidizer (generally air) in a combustion chamber, which is an integral part of the working fluid flow circuit. In an internal combustion engine the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

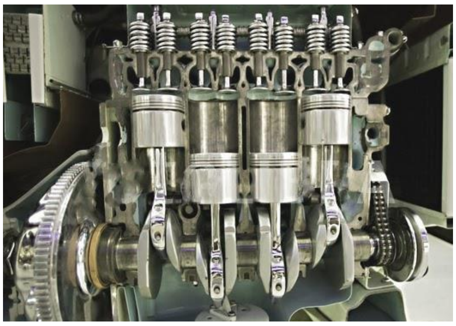


Figure 3-14: Internal Combustion Engine

Stirling Engines

The stirling engine is a heat engine that works by cyclic compression and expansion of air or other gas at different temperatures, such that there is a net conversion of heat energy into mechanical work. It is a closed-cycle heat engine with a permanently gaseous working fluid.

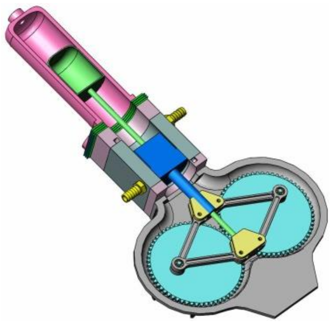


Figure 3-15: Stirling Engine

Rankine Cycle Turbines

The steam turbines utilise a Rankine cycle, which is an idealized thermodynamic cycle of a heat engine. It converts heat into mechanical work. The heat is provided from outside to a closed loop, where water is used as the working fluid.

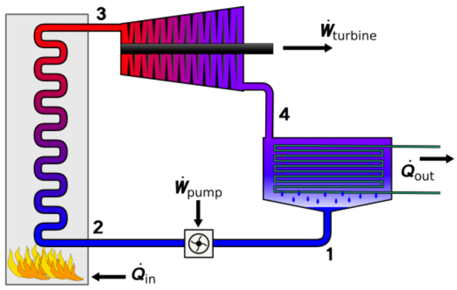


Figure 3-16: Steam turbine cycle

FUEL CELLS

A technology which converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent. Fuel cells can produce electricity continuously for as long as these inputs are supplied.

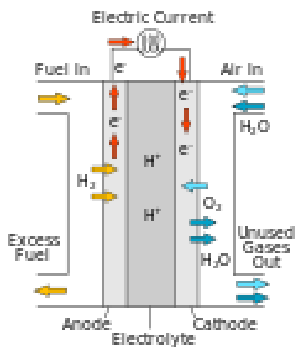


Figure 3-17: Scheme of a fuel cell

Even though all these systems can provide power outputs of relatively similar range, the different technologies do not necessary compete between each other, but on the contrary, many of them complement the others for CHP applications.

The different systems cover a wide range of thermal to electrical outputs, from very high share of heat generation for sterling engines to very high share of electrical power output for fuel cells. This inherently makes the systems appropriate to completely different environments, where the demand for heat and power are different.

As described previously, the most suitable market for MGT-CHP systems would be the lodging sector, which holds the largest ratio between thermal power requirements and energy demands. These are facilities that require a significant amount of hot water for different services provided, such as swimming pools, bathrooms, laundries and kitchens. On the other hand, healthcare facilities are also a target market for MGT-CHP systems, not only because of their high ratio between thermal needs and electricity demands but additionally these are facilities that, as lodging centres, operate all day with a continuous demand for hot water.

From the market point of view, the main competitor for the MGTs is the reciprocating engine. Generally, the latter still have slightly higher electrical efficiency, approximately 30- 34% compared to about 30% of the 100kW MGT. However, as demonstrated in the OMES project [1], using micro gas turbines brings along the following advantages:

- Lower maintenance expenses

- Lower primary emission, especially with regard to NO_x, CO and UHC
- Less space requirements, less vibrations
- Easier multi-fuel possibility
- Higher availability

3.6 Technology Challenges

3.6.1 Turbomachinery

3.6.1.1 State of the art

The turbomachinery components, compressor and turbine, are usually radial, a technology that is simple, cost effective and efficient at this power range. Even though the compressor and turbine wheels constitute the core of the micro gas turbine concept, their respective cost is relatively low due to the fact that the designs originate from the automotive turbocharger field. In auxiliary power units it is common that the turbine or even the compressor is/are of an axial type, but these units are more complex and for higher power machines, while radial turbomachinery have better efficiencies for powers up to 100 kW. [7]

From economic point of view, it is attractive to utilize existing micro gas turbine designs for biofuel fired CHP systems. However, this poses challenges that are specific to the cycle configuration. For conventional cycles, the low calorific value of the biofuels requires the use of a larger fuel volumetric flow to achieve the design turbine inlet temperature. This will significantly affect the original matching with the compressor. Considering the common turbine chocking condition, the larger fuel flow rate would lead to a lower demand of air from the compressor and, in general, increase of compressor backpressure and surge margin reduction. One option to solve the turbine/compressor mismatch is to reduce the firing temperature or blow off the excess air from the compressor, both lead to reduction in the overall cycle efficiency. Another option is to increase the swallowing capacity of the expander, by for example opening the nozzle guide vanes. This inevitably leads to change of incidence on the rotor blades and hence changes to performance. The third solution is replacing either the compressor or expander with a better-matched component.

MGT efficiency is a key factor for competitiveness in relation to alternative prime movers for most if not all application areas.

3.6.1.2 Future Research Activities

If the objective is the development of generic MGT technology strengthening the European MGT industry competitiveness, then primary focus should be on improving turbomachinery efficiency and costs. Even though global energy efficiency of micro gas turbines is usually high, due to the use of waste heat for cogeneration, electrical efficiency is slightly lower than other competing technologies. As a consequence, an effort should be made to enhance its performance. This target can be obtained by increasing the firing temperature in order to improve Brayton cycle thermodynamic efficiency or by means of an integrated and optimized design of micro gas turbine components (centrifugal compressor, radial inflow turbine,

recuperator etc). Both these approaches are object of researches even though they have different impact on machine manufacturing process. The first approach requires the use of advanced materials for the hot gas path components that are hardly implementable with radial turbomachines. On the contrary, components redesign with advanced optimization techniques enables to keep the current technology for components manufacturing leading nevertheless to important performance enhancement.
According to the ETN WG the future research activities on the turbomachinery should focus on the following topics:

Aerodynamic efficiency
Improvement of the aerodynamic efficiency using advanced fluid flow analysis and simulation.

- Geometrical design optimization of impellers, blades, vanes, volutes etc. In [8] [9] [10] [11] an example is given of a project focused on systematically increasing micro gas turbine efficiency.
- A specific aspect here is the small scale effects. Losses become increasingly large at low Reynolds numbers [12].

Tip clearance
Minimization of the tip clearance

- This involves structural design issues and also relates to rotor dynamics and bearings. Lessons learned may be taken from large aerospace axial gas turbines tip clearance control systems and through the use of new manufacturing techniques such as additive manufacturing.

Bearing losses
Reduction of bearing losses

- This may include the development of advanced bearing solutions such as air bearings.

Other non-aerodynamic losses
Reduction of other non-aerodynamic loss effects, such as windage losses and thermal losses.

Cooling
Development of cooling concepts allowing higher turbine inlet temperatures for higher cycle efficiency. The use of additive manufacturing and other emerging technologies potentially allows the active cooling of both turbine wheels and housings leading to a significantly increase of the turbine inlet temperatures (TIT).

Cost minimisation
All these developments must be accompanied with efforts to minimise costs. Apart from military applications, competitive cost levels for MGTs will be essential for commercial success. For turbomachinery, the high-volume/low cost manufacturing technology from the automotive turbocharger industry may well be adopted.

3.6.2 Combustion

3.6.2.1 State of the art

Direct or internal firing
In micro gas turbines, two different types of combustors are used: tubular and annular combustion chambers.

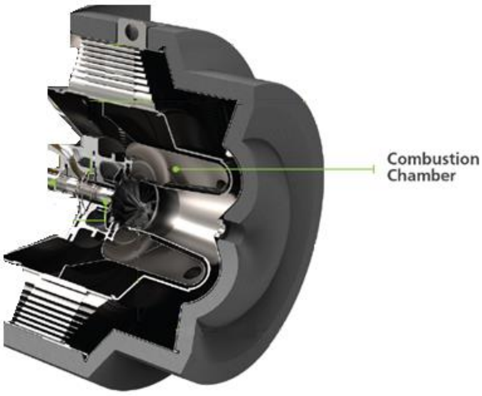


Figure 3-18: Annular combustion chamber

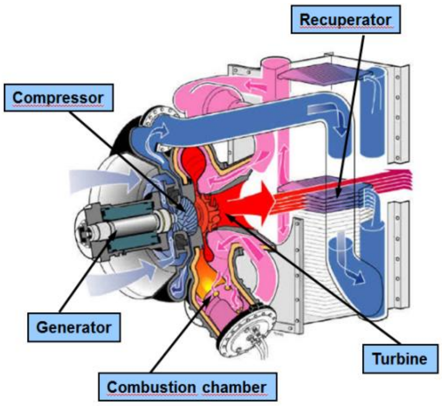


Figure 3-19: Can combustion chamber

There exist three types of combustion technologies for gas turbines, namely:

- **Diffusion flame** – is the flame which is formed between the gas and oxidizer in the boundary layer. This kind of combustion of fuels is possible only when the mixing of substrates takes place by molecular or turbulent diffusion.
- **Premixed flame** - fuel is homogeneously mixed with air, and generally burn at lower combustion temperatures (600K below diffusion flames) in order to make low thermal NO_x emissions that require high turbulence and other provisions to achieve flame stability.
- **Catalytic combustion** - It consists on combustion of fuel inside a porous ceramic medium, aiming to prevent the formation of NOx.

To stabilize the flame, usually a flow reversal pattern is created to ensure that part of the hot exhaust gases are recirculated and mixed with the incoming air and fuel. The most common way of introducing a flow recirculation is the use of swirlers. Swirl stabilized combustors are characterized by strong shear regions and high turbulence which allows a good mixing. An alternative stabilization mechanism is the jet stabilizing characterised by high momentum jets, which are discharged through orifices into the combustion chamber. The axial high momentum jet flow provides strong recirculation in the combustion chamber and leads to an intense mixing of burnt gas with fresh fuel/air mixtures. To create an inner recirculation region the orifices are usually arranged on a circular ring. High flashback resistance is obtained through the absence of low velocity zones, which favours this concept for multi-fuel application or very high combustor inlet temperatures.

Indirect or external firing

In the MGT equipped with external firing, the combustor is a component separated by the turbomachinery. Heat produced by external combustion is exchanged with air coming from the compressor in a heat exchanger.

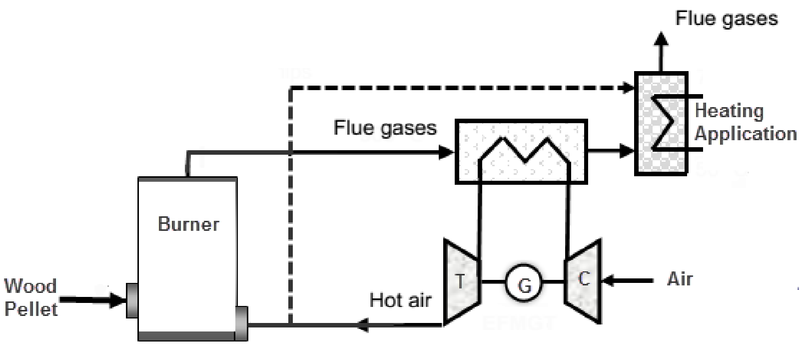


Figure 3-20: MGT indirectly fired, recuperated with recycled hot gases

Therefore the efficiency of this system is limited by the operating temperature of the heat exchanger. This solution is particularly advantageous when burning biomass, coal or other solid fuels avoiding to add a gasifier into the system.

As such, the system would be similar to a Rankine cycle but with higher efficiency. However, given the issues related to the slagging and fouling of the heat exchanger tubes, the indirect firing system has not achieved commercial success yet. Such systems have also been investigated for the firing of gas turbines with coal or other solid fuels.

Figure 3-22: The gasifier flaring the gas

Figure 3-21: MGT with external firing arrangements

Fuel Flexibility

Micro gas turbines are generally able to operate on a variety of different gaseous and liquid fuels, including natural gas, hydrogen, biogas, syngas, gasoline, kerosene, and diesel fuel/distillate heating oil.

Compared to piston engines, micro gas turbines can be operated with fuels with low heating value without engine derating. The combustion systems of micro gas turbines can also be designed in such way that it can easily burn fuels with lower octane number (increased auto-ignition / detonation tendency) as well as gases with heavier hydrocarbon components (C_2+ like Propane, Ethan, Butane, etc.) [13] [14] [15]. The same is true for fuels containing hydrogen (> 5% volume percent) [13] [16].

Most micro gas turbines are currently operated with natural gas (NG) and biogas. Usually a different design of the combustor system or an adaption of the basic design is used for different fuels.

The potential fuels for gas turbines range from conventional gaseous or liquid fuels like natural gas, hydrogen, heating oil or diesel to renewable fuels from biomass and waste fuels.

Gaseous fuels

Natural gas (also sour gas), biogas (digester gas), landfill gas, manufactured gases, hydrogen, industrial waste gas, blast-furnace gas.

Liquid fuels

Heating oil, diesel/kerosene, nafta, LPG/NGL/LNG, liquid hydrocarbons, liquid biofuels (pure vegetable oil, biodiesel, bioethanol, biomethanol, glycerine or pyrolysis oil, VOCs (Volatile Organic Compounds)).

Solid fuels (biomass and waste (external combustion))
Wood, Agricultural waste, Municipal and industrial waste.

Fuel	GCV (MJ/kg)
Biodiesel(from oilseed rape or recycled vegetable oil)	37.27
Veg. oil	39
Processed biogas	22
Agricultural waste (straw)	15.8
Animal waste	18
Waste food/fruits	15
Wood pellet/chips	17.6
Gas/diesel oil	48
Landfill gas	$22/m^3$
Natural gas	$39/m^3$

Table 3-1: Calorific values of various fuels

Emissions

Burning fossil fuels raises the concentration of greenhouse gas carbon dioxide (CO2) and other air pollutants such as unburnt hydrocarbons (UHC), carbon monoxide (CO) and nitrogen oxide (NOx), sulphur oxide (SOx). The effects of the pollutants include, among others, global warming and acid rain.

Manufacturers of gas and liquid-fuelled micro gas turbines and advanced turbine systems have bench test results showing that they beat current emission goals for nitrogen oxides (NO_X) and other pollutants [17]. Micro gas turbine systems are offering a competitive lower emission advantage in comparison to other CHP technologies.

To achieve low emissions levels at full load conditions micro gas turbine widely uses a lean premix combustion system. Lean premix operation requires operating at high air-fuel ratio within the primary combustion zone. The large amount of air should be thoroughly mixed with fuel before combustion. This premixing of air and fuel enables clean combustion to occur at a relatively low temperature [18]. Clean burning combustion is the key to both low emissions and highly durable recuperator designs. The most effective fuel to minimize GHG emissions is clearly natural gas. Natural gas is also the fuel choice for small businesses [19].

In an overview presented by B.L. Capehart [20] for micro gas turbines with the power range of 25-500kW and fuel range of natural gas, hydrogen, propane, diesel, NO_x emission is reported to be low at base load conditions (<9-50 ppm). In these systems depending to the configuration the total efficiency will be different (un-recuperated 15%, recuperated 20-30%, with heat recovery up to 85%).

	Capstone	Ansaldo	FlexEnergy	MTT
NOx [@15% O_2]	< 9 ppm	< 15 ppm	< 5 ppm	< 27 ppm (<10 ppm with FLOX)
CO [@15% O_2]	< 40 ppm	< 15 ppm	< 5 ppm	< 50 ppm (<10 ppm with FLOX)
UHC [@15% O_2]	< 9 ppm	N/A	< 5 ppm	N/A

Table 3-2: Baseload emission for different micro gas turbine system

3.6.2.2 Future research activities

Fuel Flexibility
In general all mentioned fuels can be used by a micro gas turbine to produce electric or shaft power and thermal power. Type and composition of the fuel has a direct influence on flame stability efficiency, exhaust gas emission, turbine corrosion and heat transfer processes. Furthermore, the combustion of biomass affects corrosion and slagging.

Due to the high effort in designing new combustion systems, the design combustors capable to operate with fuels over a broad range of LHV (multi-fuel combustors) would be essential. This would increase the number of production units and thus lower production costs. Here, a promising near future solution are micro gas turbines connected to a biogas micro grid, which has gained significance in the last years with the support of public funding [21] [22]. However, the use of micro biogas grids requires CHP systems that can withstand varying fuel qualities, peak demands or feeding-in natural gas to the local biogas grid to compensate for the downtime at the fermentation plants.

Especially in the CHP sector the dual fuel capability of a micro gas turbine using the same combustor design for natural gas and heating oil for example would be another promising solution to reduce the development effort of separate designs.

When different fuels are used in a micro gas turbine the combustion systems should keep the same dimensions even for fuels with a very low LHV, thus ensuring an easy exchange of combustors.

Higher fuel flexibility in terms of operational range and fuel is required also in hybrid systems. An example is the hybrid power plant, a combination of a solid oxide fuel cell and a micro gas turbine. The system requires a combustion system able to oxidize the main fuel (natural gas or, biogas) (heating value up to 50MJ/kg) for start-up and shut down procedures and the SOFC off-gas, a syngas with a very low heating value of about 2MJ/kg for base and part load conditions at very high combustor inlet temperatures up to 900°C.

A coupling of a micro gas turbine with a solar system (solar dish / solar receiver) as an example of a “fuel replacing unit” requires a combustion system ensuring stable combustion over a wide range of different air-fuel ratios and high combustor inlet temperatures to compensate the fluctuation in the solar heat input.

Another example would be the coupling of a micro gas turbine to a “fuel producing system” like an electrolysis plant or a wood gasifier. Here, hydrogen produced by the electrolysis plant in times of excessive renewable electricity can be also used as fuel.

Non-conventional MGT layouts
Further combustion related research activities depend on specific requirements for non-conventional MGT layouts (e.g. wet cycles, exhaust gas recirculation, external combustion).

Exhaust gas recirculation is used to increase either the H_2O content to increase the thermal efficiency by using the heat of condensation or the CO_2 content of the exhaust gas to enhance CO_2 capture and sequestration. To achieve a considerable increase in thermal efficiency, exhaust gas recirculation rates of far above 50% should be achieved, which is beyond the capability of current conventional combustion systems.

In a wet cycle the impact of the water injection on the combustion process has to be taken into account in the development of the combustor design.

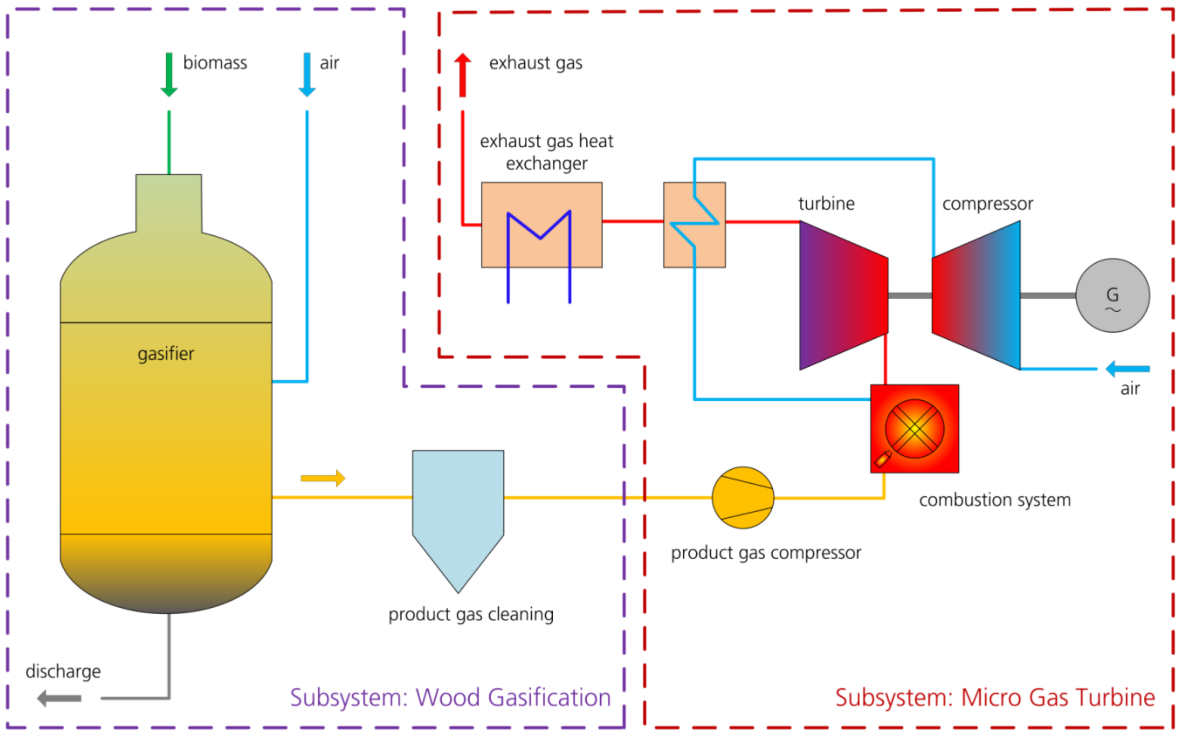


Figure 3-23: Simplified sketch of a power station concept based on a wood gasifier with a micro gas turbine

An interesting evolution of natural gas micro turbines consists on the external combustion micro gas turbines (Externally Fired Micro Gas Turbine, EFMGT) that, although still being in the development phase, could ensure the typical advantages of the gas turbines technology, together with the exploitation of a "carbon neutral" fuel.

Emission reduction

With regards to emissions, the below targets should be achieved in future research activities:

NOx < 5ppm (base load & part load 50%)

CO < 10 ppm (base load) < 20 ppm part load 50%

UHC < 3 ppm (base load & part load 50%)

As a result of the significant progress achieved by industry and research groups, combustion in gas turbines for power generation is already relatively clean. However, the combustion systems of micro gas turbines still show a large potential in emission reduction – even at the design point. In contrast to large gas turbines micro gas turbine combustion is characterized by high combustor inlet temperatures leading to high adiabatic flame temperatures. Here, various micro gas turbines demonstrated that single digit NOx values are achievable [18] [22]. On the other hand the CO and UHC values at the design point (e.g. Capstone) and or at part load conditions are rather high [18] [22]. Also, due to the new demands related to the integration of the renewable energies – primarily fuel and load flexibility – pollutants remain a main research issue at off-design or part load conditions. Here, one of the challenges is the reduction of CO at higher air-fuel ratio and thus lower flame temperatures.

That clearly indicates that further improvements of the combustor designs are necessary.

The design effort even increases especially in small micro gas turbines with high turbine inlet temperatures and moderate pressure ratio using high temperature recuperators. Here, the combustor inlet temperature may also be above the self-ignition temperature of the fuel. This increases the risk of flash back and combustor damages. The design of premixed combustion systems becomes therefore a challenge; especially in case of conventional swirl stabilized combustors. However, a high degree of premixing of air and fuel in is a must for many combustor designs to ensure low NOx emission.

Jet stabilized combustors like combustion systems based on the FLOX® concept are an exception. Here, fuel is injected in the flow direction into a high momentum air flow via a fuel nozzle. Air and fuel are partially premixed in a mixing section before the mixture enters the combustion chamber. The premixing is required to decrease the otherwise long combustion zone. The high jet velocity generates a strong inner recirculation zone which dilutes the incoming fresh gas with hot exhaust gas. This leads to a homogeneous temperature distribution without hot spots which is essential for low NOx emissions. Due to the high jet velocity the risk for flashback is significantly reduced, even when pure hydrogen is used as fuel. The development of FLOX® based combustors for micro gas turbines just started in recent years within DLR (e.g. for natural gas, wood gas or biogas) and demonstrated the potential of this combustion concept [14] [15] [22].

Combustion of the new fuels referred to above can lead to a changed event chain of pollutant formation. Therefore, optimal operating conditions for MGT combustors have to be identified in an approach using appropriate numerical tools and detailed and experimentally validated information on the underlying physics and chemistry while at the same time observing system requirements.

Especially the mixing process between gaseous fuel and oxidant, that is recognized as one of the main aspects of mixture preparation and greatly affects flame characteristics, is dominated by turbulence. For this reason, as far as concerns the advanced numerical simulations of combustion phenomena, modelling unsteady behaviour of lean premixed combustor, Large Eddy Simulation methodology in conjunction with combustion models has to be investigated, since LES has contributed largely to the understanding of the very complex turbulence-combustion interaction process.

3.6.3 Materials

3.6.3.1 State of the art

Recuperator

The recuperator is one of the critical components in micro gas turbine systems and is responsible for a significant fraction of the overall efficiency.

In fact, two parameters have potential for efficiency advancement: (i) increasing the turbine inlet temperature and (ii) higher recuperator effectiveness.

Recuperators are classified by their method of construction into three basic types: shell-and-tube, plate-fin and primary surface recuperator (PSR) [23] [24] [25]. All of these high temperature heat transfer systems have a common requirement for high materials performance.

Figure 3-24 – Annular PSR recuperator

Since the thermal efficiency of a recuperator generally increases as the air cell wall thickness decreases, thinner foils, and thus alloys with good high temperature strength, are desired. In addition, the alloy foils must be able to withstand extreme deformation during manufacturing process of the air cells. Therefore the fine-grained alloy foils are required that must have high creep strength at the maximum operating temperature.

Most turbine recuperators currently in production operate at a maximum temperature ranging from 600°C to about 750°C [26].

The other property that the recuperator materials must provide is an excellent oxidation resistance. As a result, alloy systems that could be considered for this duty include: austenitic stainless steels, ferritic steels (e.g. FeCrAlY alloys and their ODS variants) and nickel-based alloys (with high chromium and/or aluminium contents).

An example alloy used for recuperator applications, in particular by ANSALDO, is MA 253, that is an austenitic chromium nickel steel alloyed with nitrogen and rare earth metals. The grade is characterized by:

- High creep strength
- Very good resistance to isothermal and, particularly, cyclic oxidation
- Good structural stability at high temperatures
- Good weldability
- Maximum operating temperature is approx. 1150°C (2100°F).

Rotor and Stator for Turbomachinery

For micro gas turbines stator, Alloy 713C is used in ANSALDO engine.

It is a precipitation hardenable nickel-chromium base cast alloy, with excellent strength properties up to 1800°F (982°C). This alloy is characterised by good castability, remarkable resistance to oxidation and thermal fatigue, and outstanding structural stability [27].

The state-of-the art rotor materials are Ni-based superalloys, such as MAR-M-247 [28] used by ANSALDO (MAR-M is a registered trademark of Martin Marietta). Mar-M 247 is a polycrystalline cast nickel base superalloy. It is commonly produced using directional solidification techniques to improve creep rupture strength. It has high temperature strength, corrosion and oxidation resistance. HiETA Technologies are currently developing capability to Additive Manufacture both CM247LC and Haynes 282 for use in high temperature turbomachinery and recuperators, a process that will also enable cooled turbine wheels for increased operating temperatures (potentially 1200ºC or more).

3.6.3.2 Future Research Activities

The future of materials for MGT is currently oriented in two directions: metallic materials on one side and ceramic materials on the other. While metallic materials is currently the only choice in the market and a proven solution, ceramic materials bear the potential for higher speed and firing temperatures thus providing higher efficiency.

Ceramic gas turbine development activity has been ongoing since the 1950s, heavily supported by governments in the United States, Japan, the countries of the European Union, and those of the former Soviet Union. Primary drivers for the programs were promises of improved high temperature durability, compared to superalloys, improved engine performance, light weight, and independence from strategic elements Co, Cr, Ni, etc. Rig and engine testing during the early development work, typically for up to several hundreds of hours, showed good potential for performance improvements with ceramics. However, long-term engine tests that started in the 1990s, conducted for many thousands of hours at field demonstration sites, revealed shortcomings (e.g. material resistance) that severely dampened the enthusiasm of the gas turbine designers for ceramics. [29]

Even though throughout decades of research and large investments there has been no breakthrough for ceramic materials to overcome its main shortcomings, new technologies improvements, in particular additive manufacturing techniques could improve the cooling of the components and ease the material strains, therefore solving some of the major issues found for ceramic materials.

Recuperators

In developing heat exchangers for micro gas turbine systems, it is necessary to consider that they have to comply with space and layout restrictions that markedly affect the conceptual design of the recuperator. In addition, they have to withstand the constant temperature differentials across the surface area, and have to match an operating life of several thousand hours with hundreds of start-up/stop cycles. It is also very important to balance the need for higher performance and more durable materials with the need to make them as cost effective as possible and reduce pressure losses [30].

Metallic Materials for Recuperators

During last 10-15 years, intensive research activity has been carried out to identify and evaluate candidate alloys that could meet the performance requirements. A significant effort in this topic has been spent in particular by ORNL, also sponsored by the US Department of Energy (DOE) in the frame of an Advanced Microturbine Program [30].

The higher performing and also more expensive alloys can be divided into two different groups [25]:

- Alloys comparable with 347 stainless steel: modified Alloy 803, Alloy 602 CA, Haynes HR120, Haynes HR230.
- Alloy considerably stronger than 347 SS: Alloy 625, Haynes HR214, Hastelloy X, Plansee alloy PM2000 (ODS alloy).

In this classification alloy 740 represents a sort of dividing line.

Alloys 625 and 718 are currently available as Additive Manufactured materials, with 282 and 247 are also currently being developed by HiETA Technologies for high temperature recuperator application, offering high strength and corrosion resistance at elevated temperatures (1050°C or more).

Composite Materials for Recuperators

Solid materials holding promise for use in heat exchangers can generally be divided into four categories: polymers, metals, ceramics and carbonaceous materials. In many heat exchanger applications, these materials perform satisfactorily in their unmodified or non-reinforced form. However, in some applications advanced structural materials are needed to be stronger, stiffer, lighter in weight, and more resistant to hostile environments. Composite ceramic materials offer engineers an ability to create a limitless number of new material systems having unique properties that cannot be obtained using a single monolithic material. This approach to construction holds tremendous promise for future heat exchanger designs rather than selecting a single material, multiple materials may be selected and then tailored to meet the specific requirements of the application. Composite materials are constructed of two or more materials, commonly referred to as constituents, and have characteristics derived from the individual constituents. The constituent that is continuous and which is often, but not always, present in the greater quantity in the composite is termed the matrix. The second constituent is referred to as the reinforcing phase, or reinforcement, as it enhances or reinforces the properties of the matrix. By combining matrices with thermally conductive reinforcements such as special carbon fibres, SiC particles and diamond particles, it is possible to create new materials with high thermal conductivities and a wide range of coefficients of thermal expansion (CTEs) [31].

So far, regarding heat exchanger recuperators for high efficiency micro gas turbines the available literature suggests as best option the application of silicon carbide for the manufacturing of this component.

Rotor and Stator for Turbomachinery

When burning biofuels in a MGT, both rotor and stator are confronted with a harsher environment as the composition of the combustion products are more aggressive and accelerate the corrosion process. The problem is common to both metallic and ceramic rotors. The simplest and common choice to overcome the corrosion issues is to modify the coatings instead of modifying the base alloy.

If the MGT is running with solar energy source, the temperatures achieved in such systems are low (800ºC). In this case, there is no interest in using ceramic material to increase efficiency as high temperatures are not reachable. The factor limiting the maximum temperature is currently the receiver technology. Additionally, corrosion issues are minor due to the low temperatures and the clean working fluid (air without fuel burnt). However, if a hybrid fuel-solar system is considered in order to make it a dispatchable-energy unit, corrosion issue would be the same as in any other MGT:

Metallic Materials for Rotor and Stator

Cast superalloys, providing an outstanding balance of high temperature strength, fatigue resistance, oxidation resistance and coating performance and that can be manufactured to high tolerances in complex configurations, are commonly used in the most demanding applications of aero and industrial gas turbines and their use is expanding also to smaller micro gas turbine engines.

Therefore, during last years, the application of cast Ni-base superalloys has been investigated and the process capability to small turbine has been evaluated by Cannon-Muskegon Corp [29].

A range of alloys has been considered encompassing nickel, iron and cobalt alloys that can be utilized structurally at operating temperatures of up to 900°C.

They include conventionally cast, equiaxial (EQ) alloys, directionally solidified (DS) and the more advanced single crystal alloys (SX).

The use of light metallic alloys such as Titanium Aluminide for the turbine impellers could be beneficial in some MGT applications. Light-weight turbine impeller could improve the dynamic stability of the rotor assembly in applications with wide range of operating speeds. One example is the MGT for Concentrated Solar Power, where the MGT operates on wide range of speed because of variation in the received solar power.

Gamma type Titanium Aluminide (γ-TiAl) is the main candidate in this range of alloys. They have interesting mechanical and thermal properties in high temperatures up to 950°C. There are big advancements in manufacturing process for turbomachinery components using this range of alloys using Additive Manufacturing.

Ceramic Materials for Rotor and Stator

Silicon nitride is up to now the ceramic material designated as the preferable one for the manufacturing of rotor components (including rotating and static parts). Most of the silicon nitride investigated for this kind of application are materials sintered with the addition of Yttria and Alumina, but the material considered as the most resistant from the mechanical point of view is a silicon nitride produced by Kyocera with addition of Lu compounds and identified as SN281 or SN282 (respectively for application in rotating and static parts) depending on the sintering procedure applied for manufacturing. Two prototype micro-rotors have been produced and largely characterised at ORNL (as parts of a U.S. DoE supported program on distributed energy): one rotor has been manufactured for an Ingersoll Rand machine project while the other one has been manufactured by UTRC in a machine project developed in agreement with Pratt&Whitney Canada. The following figures show micro-rotor prototypes [32].

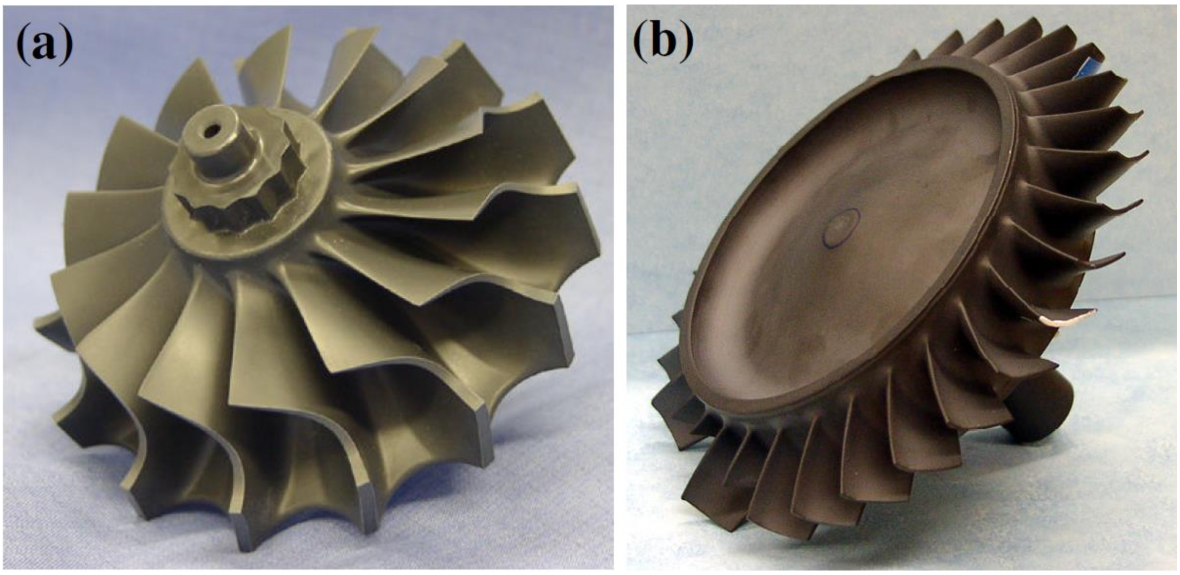


Table 3-3: MGT's rotor prototypes

3.6.4 Recuperator

Different recuperator technologies have been developed, tested and used over the last decades. This paragraph tends to sum-up and review some of them.

3.6.4.1 State of the Art

Different recuperator technologies have been developed, tested and used over the last decades. This paragraph tends to sum-up and review them:

- ACTE: annular type recuperator, primary surface, counter-flow. Millimetric hydraulic diameter, washboard corrugated pattern, local pressure retention. Fully laser and TIG welded. Metallic (typically 3xx, austenitic SS series). ACTE cores are obtained by the coiling of a pair of patterned sheets. Air and gas flow parallel to the coiling axis. Headers are welded on each side of the cylinder to distribute and collect compressed air radially.

- Bosal: Primary surface, millimetric hydraulic diameter, counter-flow, inclined corrugated pattern stimulating micro-turbulences by shear layer to improve heat transfer. Fully stainless steel high alloyed foil typical 3xx applied in series, and also demonstrated with creep resistant Inconel and alumina forming grades. Rectangular type cells, fully laser-welded, stacked in rectangular box type core with easy modular sizing in line with customer specifications based on number of cells. Progressive embedding of thin foils (thickness hundred of microns) up to manifolds with thickness of multiple millimeters. Designed for minimal thermal bridges to have 90% effectiveness. Manifold design with CFD-verified flow uniformity. Cold start-stops resistant design and proven in accelerated tests. Range covering 10-250kWe devices. European Pressure Equipment Directive certified unit according PED 2014/68/EU for serial production. Design accumulated already more than 3 million hours in the field.
- Capstone: Trapezoidal welded air cells, stacked in an annular way to achieve a annular, primary surface, counter-flow heat exchanger. Millimetric hydraulic diameter, wavy channels. Metallic (typically 3xx, austenitic SS, HR120 or Inconel series). Flow parallel to the annular axis. Compressed air distribution via the internal diameter.
- HiETA: Additive Manufactured typically Inconel recuperators featuring optimised secondary surfaces and integrated manifolds/ducts. Recuperators can be annular, rectangular or any other shape, and due to highly effective secondary surface features significantly smaller than conventionally manufacture alternatives, making them cost effective also.
- MTU: Shell&tube heat exchanger. Tube with an elliptical cross section. Tube for instance bended in a U configuration to achieve a counter-flow arrangement. Tubes ends brazed on 2 end plates to distribute and collect compressed air. Metallic (typically 3xx, austenitic SS or Inconel series).
- Solar: plate and fins (primary + secondary surface). Stack of plates ending in a rectangular shaped recuperator. Air distributor and collector welded on the core. Counter-flow arrangement. Millimetric hydraulic diameter. Metallic (typically 3xx, austenitic SS series).
- ToyoRadiator: plate and fins (primary + secondary surface). Stack of plates ending in a rectangular shaped recuperator. Air distributor and collector welded on the core. Counterflow arrangement. Millimetric hydraulic diameter. Metallic (typically 3xx, austenitic SS series).

3.6.4.2 Future research activities

A gas turbine recuperator is a gas to gas heat exchanger for recovering gas turbine exhaust heat for pre-heating combustor entry air in order to save fuel. In terms of (usually counter flow) heat exchanger design, the combination of requirements imposed by the gas turbine cycle makes successful development of a recuperator an extraordinary tough challenge. These requirements include:

1) High effectiveness (typically >80%).

2) Low pressure losses (typically not more than a few % (<2-4%) for both hot and cold flow paths (pressure loss and effectiveness can be often exchanged: high effectiveness can often only be obtained with relatively high pressure loss for the same volume).

3) Resistance to high temperatures (steady state: creep life and corrosion resistance). Depending on the turbine inlet temperature and turbine efficiencies, general trends for the hot inlet max temperatures are:

    a) With high cycle pressure ratios (>5) usually 650-700˚C (stainless steels).

    b) Low cycle pressure ratios (<4) >750˚C (advanced/nickel based high temperature alloys).

4) Resistance to thermal shock and large temperature gradients in the structure (low cycle fatigue life).

5) Large pressure difference between hot and cold flow. For example, with a cycle pressure ratio of 7 it would be 6 bar, meaning significant structural loads in the heat exchanger matrix

6) Compact / low weight design.

7) Minimal heat loss (insulation).

8) Affordable costs:
    a) Minimal use of expensive materials.

    b) Low manufacturing costs.

9) Recuperator operation in mobile systems

In order to improve the know-how associated to recuperators in Europe, different work areas have been identified. Those are

1. WP1 Thermodynamic optimization
2. WP2 Gas composition and anti-fouling channels geometries
3. WP3 Materials
4. WP4: Cost minimization

Thermodynamic optimization

The recuperator parameters that mainly affect the overall efficiency of the MGT are the effectiveness and the pressure losses. If the effectiveness increases (maintaining that same heat transfer coefficient), the exchange surface is higher, so the recuperator is larger. With the same exchange area, the heat transfer coefficient is higher with more turbulent flows (and/or with secondary flow structures), but the pressure losses increase too.

This means that geometry of the exchange surfaces must be optimized in order to find the best compromise (in term of overall efficiency of the machine) between heat transfer, compactness and pressure losses.

3D-trade-off regarding recuperator effectiveness, backpressure and cost.

1) Literature: collection of gas-to-gas heat transfer coefficient and pressure drops laws.

2) Micro-channel CFD analysis to validate the laws in the recuperator conditions

3) Local optima - What could be local optima within this 3D-space?

4) Global optima - Is there a global optimum feasible? Can a perpetuum mobile be reached?

5) Matching Recuperator systems to the application.

Gas composition and anti-fouling channels geometries

Compatibility of the recuperator with the turbine fuel flexibility.

1) Exhaust gases characterization - Physical properties of the gas: Cp values, viscosity, particles characterization, condensation behaviour, etc.

2) Sensitivity of the recuperator regarding contamination and performance loss (effectiveness and pressure drop) due to exhaust impurities. Anti-fouling methods (description, test: pyrolysis, vapour, etc.).

3) CFD analysis to validate fouling.

4) Possibility of Cleaning of recuperator systems

Cost minimization

Another issue related to the surfaces is the manufacturing process: the geometry of the heat exchanger and the assembly process of its parts, must be compatible with automatic machining/assembling techniques. The primary surface type appears today the best solution from the point of view of cost and reliability.

Cost reduction of recuperator is achievable implementing the following actions:

1) Determine possibilities of cost reduction potential by high volume effects
    a) Based on modularity.
    b) Based on standardization.
    c) Based on compactness.
    d) Based on automation in serial production.
    e) Based on others.

2) Determine possibilities of cost reduction potential by process and material selection.

3) Identify total value cost reduction possibilities by advanced integration with a specific engine.

4) Integration of recuperator systems in the process.

5) Determination of influence factors of emission reduction.

3.6.5 System Integration

3.6.5.1 State of The Art

Currently, the system layout for commercial micro gas turbines with the largest number of machines is based on a recuperated Brayton cycle.

Regarding innovative MGT applications, especially for the integration of renewable energy sources with MGT, different possible component integration activities are under development. However, all the innovative solutions proposed to improve MGT performance are just related to research activities because they are far from commercial level for cost or technological issues not completely solved. At the moment the following innovative systems layout are under analysis from both theoretical and experimental point of view:

- Hybrid Cycles
    - Based on integration with high temperature fuel cells
    - Based on integration with Concentrated Solar Power (CSP)
- Integrated Cycles
    - Integration with energy storage technology
    - Integration with bottoming cycles
- Non-Conventional Cycles
    - Wet cycles (especially micro Humid Air Cycle (mHAT) plants)
    - Inverted Brayton Cycle

Even if prototype devices were successfully developed, the component integration is not completely solved for the following issues: compressor instability, costs related to high temperature components, control system development, additional constraints due to sensible components (e.g. the SOFC), exceptional complexity level, reliability, etc.

3.6.5.2 Future Research Activities

As described previously, current development for power generation is following two main trends: towards smaller distributed units and plant integration into wider energy systems. Wider energy systems consist of an integration of various energy sources or plants with a clear trend towards high efficiency, renewable energy and utilisation of low exergy flows, such as coupling electrical and thermal systems (e.g. district heating). In this context, MGTs are positively competing against internal combustion engines in terms of low maintenance, noise and especially emissions. Furthermore, they are interesting devices for development of advanced plants, such as for example hybrid systems based on fuel cell technology.

MGT designs available in the market currently present a compact and integrated design of all its components in order to improve the MGT efficiency and operation in conventional recuperated Brayton cycle. However, this acts against the ability of the MGT to be integrated or hybridised with other technologies, making it more complex and expensive to open and modify the cycle. Therefore there is a particular need to design MGT for integration in order to increase the flexibility of the system regarding the cycle.

As a consequence MGTs and the MGT cycles need further development towards:

- Higher electrical efficiency;
- Increased flexibility for integration with other systems;
- Increased flexibility towards the utilization of various sources of energy.

Therefore future development activities should consider the following three aspects:

1) Improvement of current cycles and new advanced cycles;
2) Development of the necessary technologies to allow the design of advanced and new cycles;
3) Design of MGTs according the needs of the new processes and their integration into other cycles.

The evaluation and R&D activities connected to advanced cycles is usually closely connected to specifically chosen type of cycle and, thus, they cannot be subject to generate some ideas for general R&D activities and possible projects. However, an interdisciplinary approach is essential as already mentioned above.

The different system configurations that require development for the advancement of the MGT technology fall within three categories: Hybrid Cycles, Integrated Cycles and Non-Conventional Cycles. Hybrid Systems are configurations where the traditional MGT cycle is opened to include a different technology in-between. Integrated Systems refers to cycles where the MGT can still be considered as a single unit that is being connected with other cycles or technologies. Non-Conventional Cycles include cycles strictly for the MGT technology that are different from the Brayton and recuperated Brayton cycle.

Hybrid Cycles

Important issues have to be analysed on the MGTs for hybrid systems, such as cycle layout (including MGT and component optimisation), system dynamic aspects affecting the machine (especially surge problems due to the connection with a large volume), MGT control system issues to manage all the additional constraint problems and other interaction aspects with the other technologies (e.g. fuel cell, CSP).

Unexpected issues might arise when integrating the MGT with other equipment due to the exception of gas turbines from the pressure equipment directive (directive 97/23/EC under 3.10). Especially when the MGT is integrated with a large volume such as a fuel cell, a humidification tower for a wet cycle is a conflict rising based on the fact that the volume and connected components need to fulfil the requirements of 97/23/EC. Due to this conflict might it be necessary to add or integrate additional components such as additional fast shut off and/or blow off valves, additional pressure boundaries, different and certified elements in the fuel system to only name a few of them. This conflict might in consequence results in significantly increased costs having an impact on the techno-economical feasibility of the concept.

MGT-SOFC Cycle

Due to the importance of future perspectives (linked with high efficiency - higher than 60% in small scale units-, low emissions -almost zero in case of fuel from biomass- and potential applications in the distributed generation paradigm) special attention has to be focused on

Solid Oxide Fuel Cell (SOFC) based hybrid systems. Even if different layouts are possible, the plant scheme based on a pressurized SOFC seems to be the most promising for efficiency point of view.

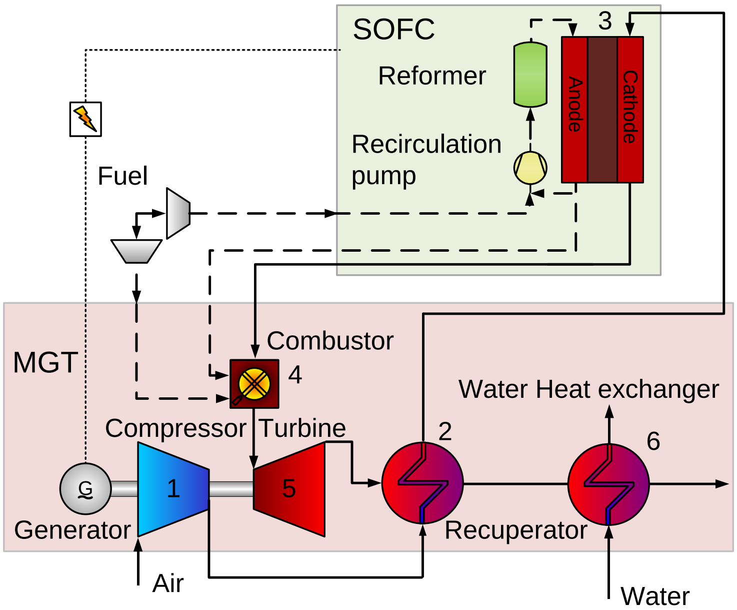


Figure 3-25: Generic plant layout for a SOFC base hybrid system

As shown in Fig.3-26, the system is based on the coupling of a SOFC stack with a micro gas turbine equipped with a recuperator (other configurations are possible without the recuperator, but including also a cathodic recirculation). So, as in Fig.1, air is compressed and preheated upstream of the cathodic side of the fuel cell. On the anodic side, fuel is mixed with a recirculated flow (performed here with a single stage ejector) containing a large amount of steam for the reforming reactions necessary to produce a hydrogen rich fuel. These are performed internally inside the anodic ducts or just upstream of the fuel cell inlet. The not oxidized fuel in the SOFC ducts reacts with the cathodic exhaust flow (the oxygen) in the Off-Gas Burner (OGB) located upstream of the turbine (or in the recirculation line in case of a cathodic loop). Finally, the exhaust flow is used in the recuperator for fresh air pre-heating. Moreover, in co-generative plants a further heat exchanger can be installed to produce hot water (or steam) to satisfy thermal loads. The power generation is carried out in the stack (DC power to be converted in AC with an inverter) and in the machine alternator (AC and high frequency power to be converted thanks to the machine power electronics).

Even if the system concept is well known, these plants are not ready for commercialization for different problems not completely solved, such as high costs, low reliability, issues related to the SOFC coupling with gas turbine technology, control system aspects. So, further research activities are necessary not only for natural gas based solutions, but also for biofuel/syngas plants. In comparison with prototypes working with natural gas, a complete re-design of the fuel system has to be carried out involving also the anodic recirculation line (including the ejector). Moreover, the operation with a large amount of inert gas in the fuel duct can produce additional surge risks to be carefully evaluated and prevented.

MGT-CSP Cycle

For the CSP part in a system perspective it will be important to include hybridization with biofuels as one way to achieve plant availability. Compared with other systems the gas turbine might be the easiest and most efficient technology in terms of solar/other fuel hybridization.

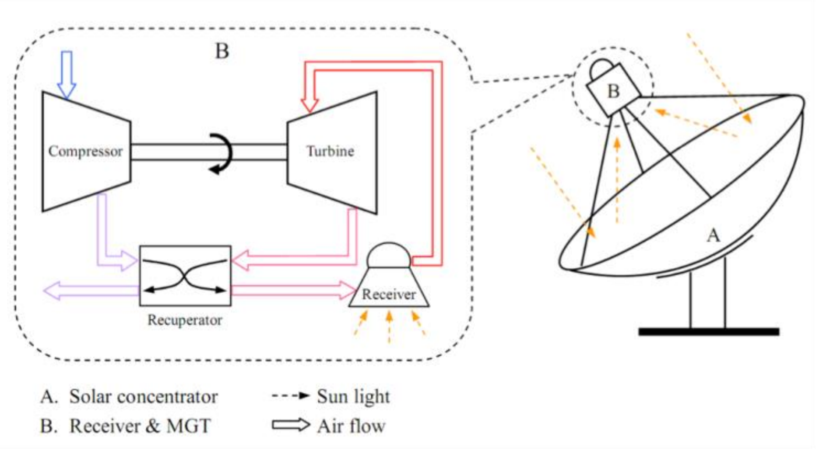


Figure 3-26: OMSoP plant configuration

In the combustion side one important aspect from the CSP side is the combustion chamber/ solar receiver integration. This demands new technology solutions and should be part of the hybridization heading for flexible fuels, where solar is one type of fuel.

Integrated Cycles

Integration with Bottoming Cycles

MGT may be integrated with bottoming cycles (e.g. ORC (Organic Rankine Cycle) or others) to increase electrical efficiency.

Energy Storage Integration *Renewable Energy Source*

Combination of the MGT with energy storage technologies and systems to be better suited for different time pattern of demand for e.g. electricity and/or heat. This also supports the integration of fluctuating renewable sources, such as equipping CSP plants with high temperature energy storage systems. There are extensive applications of MGT in co-generation and smart grids including generation of cooling power towards absorption chillers. Even if this point is mainly related to integration of existing technologies, optimisation of the whole system will be essential for efficient management.

Non-Conventional Cycles

Wet Cycles

Wet cycles, as one type of advanced cycles, are processes with extraordinary high water content in the work fluid (e.g. humid air turbine, TopCycle etc.). There are some general aspects related to these cycles which might be topic of R&D activities, as reported in the following points:

- The combustion process and design in case of water injection and the operation and stability aspects (e.g. surge margin) have to be improved.

- The challenges when connecting the GT to bigger volumes for the purpose of humidification and the resulting change in transient behavior as well as during start-up and shutdown operations need to be considered in close connection with the development of wet cycles.

- Topics related to water recovering at MGT discharge duct have to be highlighted especially for applications with low water source.

- Effect of water on the components, especially on the recuperator: lifetime, performance, etc.

- Humidification of MGT in order to increase the electrical efficiency in moments of low heat demand.

Inverted Brayton Cycle

Inverted Brayton cycle (IBC) for very small units (electric power of less than 2 kW, no turbochargers available) or for small units (up to 30/50kWe) using very low caloric fuels containing hydrogen (e.g. wood gas); this eliminates the high power needed for the fuel compressor and the technical and economic problem of compressing hydrogen fuels.

MGT Design for New Processes

Most current MGT designs target a compact MGT with closely integrated and connected components (compressor, combustor, turbine, recuperator) which makes it challenging to integrate them into other processes. The design differs from systems designed for integration (e.g. turbochargers) and therefore needs to:

- Be able to match different compressor and turbine specification (e.g. for various mass flow differences);

- Design recuperators resilient to changes in flow composition and load. Current recuperators are optimised for ‘normal’ operation of MGTs. This makes it difficult to ensure optimised operation when for example injecting water in the system. More resilient recuperators may introduce a small efficiency penalty when working in ‘normal’ conditions but could better adapt to changes in MGT load and flow composition to ensure a higher overall efficiency;

- Connect to other components (flange dimensions, positions and forms);

- Cover different main operating profiles via versions for peak load efficiency (i.e. base-load operation) and those optimised for more or less continuously changing operating conditions (compromise in peak load efficiency for the benefit of a flat efficiency characteristic).

As consequence a new MGT design has to be linked with systems integration aspects considering the following main issues:

- Modular and open design to allow to:
    - integrate other heat sources (e.g. CSP, high temperature waste heat) while still keeping the combustor;

- easily exchange combustor part to comply with different fuels as well as the above-mentioned complementary firing;
- design aspects to use exhaust heat for various other purposes;
- easily integrate components based on high flexibility (e.g. flanges or tee joints to connect additional components);
- obtain the specific MGT performance requested by advanced cycles, such as hybrid systems based on fuel cells.

- More open control system to:
  - enable integration into a different system or cycle;
  - allow connecting additional signals;
  - operate the integration with controllers related to additional components (e.g. fuel cells, water injection unit, EGR);
  - allow including other safety relevant signals to protect other connected components;
  - eventually allow for controlling additional functions (e.g. second combustor, additional valves etc.);
  - be interconnected to other controllers in the energy systems either as master or as slave, which might also require the exchange and transfer of additional/more signals;
  - implement innovative control approaches, such as Model Predictive Control based solutions;
  - allow an easy integration with external and/or additional diagnostic tools.

- Techno-economic analysis to:
  - understand the validity of all new system/cycle developments in a future energy system;
  - evaluate the technology potential cost in terms of LCOE.

Opportunities exist to utilise new and emerging manufacturing techniques such as Additive Manufacturing to allow better integration of components for reduced losses, increased thermal efficiency and reduced weight/cost, and to allow multiple design variants to be generated without tooling costs and setup times.

3.7 INTERNATIONAL DEVELOPMENTS

This paragraph is intended to list the main, but not exhaustive, EU co-funded projects on MGTs.

PROJECT	LINK
BIO-HYPP	**Biogas-fired Combined Hybrid Heat and Power Plant** The Bio-HyPP project aims to develop a full scale technology demonstrator of a hybrid power plant system – a combination of solid oxide fuel cells (SOFC) and a micro gas turbine (MGT) – using biogas as main fuel in lab environment.
BIOMGT	**BIOMGT** The BIO_MGT project aimed to demonstrate the technical feasibility and to evaluate the performances of a small polygeneration unit based on micro gas turbine (MGT) fed by woodchips.
BIOTURBINE	**Opportunities for biofuel-burning Microturbines in the European Decentralised-generation Market** The aim of the project was to assess the technical feasibility and the market potential of microturbines that run on liquid biofuels (bioturbines) for power and heating applications (CHP).
CAME-GT	**Thematic network for cleaner and more efficient gas turbines** The objective of this Thematic Network (TM) was to coordinate RTD projects in industrial gas turbines, including projects from FPIV and FPV covering fossil fuels and biomass; and gas turbines in CHP applications and combined cycles.
CHEP	**Research and development of high efficiency components for an intercooled, recuperated CHP gas turbine for combined heat and efficient power** The project aimed to the initial development phase of gas turbine cogeneration unit capable of meeting current market requirements in terms of power output, efficiency, reliability and cost.
ELEP	**European Local Electricity Production** ELEP set out to support the use of DG in Europe by removing the regulatory and practical barriers currently restricting its use and by developing a roadmap and timeline for its take-up. The project set out to identify and address the barriers affecting DG use and to propose solutions and methods by which the barriers could be minimised through policy and legislation. Another key objective was the establishment of detailed EU policy guidelines on connection charging, ownership of equipment, net metering and feed-in tariffs.

E-TRIGEN	**Trigeneration and integrated energy services in South of Europe and Brazil** The project demonstrated an innovative integration of three technologies: micro turbine, hot water fired absorption chillier and ice storage thermal system and aims to demonstrate the main benefits resulting from the activity of Energy Services Companies while using the micro trigeneration systems and a flexible financing mechanism.
IM-SOFC-GT	**Integrated Modelling study of FC/GT hybrids** The main objective of the project was to develop the capability to assess the performance of FC/GT hybrids using a close integration of system and stack models and set performance requirements for FC/GT hybrid based generation systems through a technology characterisation.
IRMATECH	**Integrated Researches on MAterials, TECHnologies and processes to enhance MCFC in a sustainable development** The IRMATECH project aimed at several industrial objectives: 1. Cost reduction of MCFC from about 8000 to about 1000 _/kW for the whole plant in the next 10 years through: - reducing costs related to materials and manufacturing processes of 50%-70% - increasing the compactness of the MCFC of 40% 2. Increase the long term behaviour from 20000 hours to 40000 hours 3. Minimisation of the environmental impact and used energy relating to some manufacturing processes These three major objectives will be achieved by working on the following aspects : a. Fuel Cell System: reduced manufacturing costs and increased life-time; b. Balance of plant: multifuel capability - one unique reactor for all the fuels; c. Integrated system analysis.
OMES  	**Optimised Microturbine Energy Systems** The project showed that the technology is reliable and working satisfactory. Still work must be done to reduce costs before the micro turbine will get a fully commercial break through. The original goals for power efficiency and overall efficiency were to achieve ≥30% power efficiency during full load operation overall efficiency ≥80% (ref. LCV).
OMSoP	**Optimised Microturbine Solar Power System** The overall objective of this project was to provide and demonstrate technical solutions for the use of state-of-the-art concentrated solar power system (CSP) coupled to micro-gas turbines (MGT) to produce electricity. The intended system will be modular and capable of producing electricity in the range of

	3-10 kW. The aim is to make such a system available to provide energy needs for domestic and small commercial applications.
SLUDGE2ENERGY	**A way to energy-autarkic operation of sewage treatment plants** The aim of the SLUDGE2ENERGY project was to demonstrate the decentralised reuse of sewage sludge in an efficient small-scale heat and power generation plant on the premises of the wastewater treatment plant (WWTP). The innovative sludge processing technique was intended for market introduction. The energy self-sufficient plant would reduce the amount of sewage sludge for disposal to 1/8 of the dewatered sludge.
MOCAMI	**Innovative cost-effective hybrid system based on integration of a MCFC and a gas turbine for high efficiency dispersed CHP generation** The project aimed at developing and demonstrating a small-sized hybrid system with the combination of the MCFC technology and of micro gas turbine (MTG). The development of such a small-sized hybrid system will allow lowering the production costs through the development of new and simpler processes with a better quality control and a higher yield for the different components.
SOLHYCO	**Solar-Hybrid Power and Cogeneration Plants** The scientific and technological objective of the SOLHYCO project was to develop and test a highly efficient, reliable and economic solar-hybrid cogeneration system based on a 100 Kw microturbine, able to operate in parallel on varying contributions of solar power input and fuel. A new receiver concept, based on an innovative receiver tube configuration, shall improve performance and reduce system cost. Enhancing the combustion system to multi-fuel capability including bio-fuels shall allow operation with up to 100 % renewable energy sources.

4 EXPECTED IMPACTS

4.1 ENERGY SAVING

Primary energy saving is one of the key European goals in current policy for the future years. In this context, micro gas turbine embodies a significant contributor to achieve this target.

In an EU context where the demand for heating power amounts to 50% of EU energy consumption and where 45% of that energy consumption is used in residential sector[2], micro gas turbine CHP systems can easily justify their place in the future energy sector.

With the ability to attain overall efficiencies above 90% (electrical efficiency of more than 30% with the heat exchanger), MGT with micro-CHP units meet the demand for heating, space heating and/or hot water (and potentially cooling) in buildings, while providing electricity to replace or supplement the grid supply. This would diverge from the conventional power generation where electrical output is produced in power stations of electrical efficiencies typically between 35% and 40%. On the other hand, thermal outputs are generated locally with boilers of around 80% efficiency. Currently, there are more than 100 million boilers installed in EU homes.
The study conducted within the CODE 2 project shows that Micro-CHP systems that can reach over 80% efficiency are able to save on energy losses related to long distance electricity (8-10% losses) and heat (10-15% losses) transportation. In this context, as shown in figure below, for a same demand of 260 units (160 thermal and 100 electrical) the conventional generation methods would require 465 units of fuel to deliver the demand. However, a CHP system could deliver both outputs for just 325 units of fuel, resulting in a potential 30% energy savings.

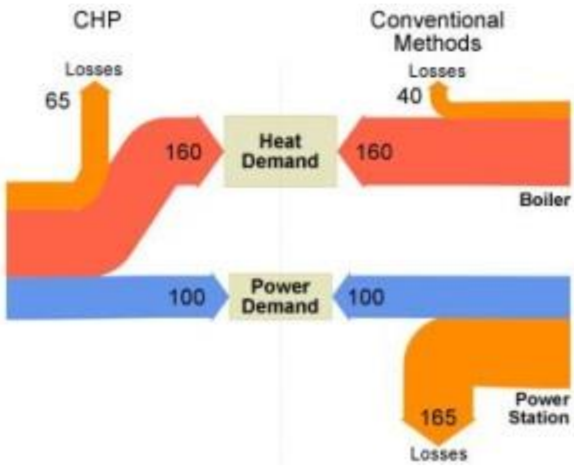


Figure 4-1: Comparison energy losses micro-CHP and conventional systems

Depending on the regulatory arrangements in place the electricity produced by micro-CHPs could be sold to the local supply network, partnering with intermittent renewables to balance supply and demand and provide further services to the grid.

[2] Source: EC- An EU Strategy on Heating and Cooling, 16 February 2016

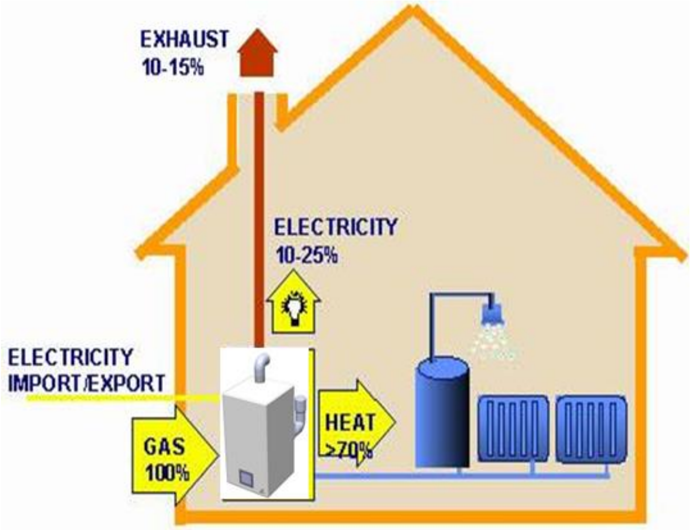


Figure 4-2: micro-CHP systems for residential

The heat generated could be used on-site (maybe in combination with gas fired boilers) and/or supplied to other homes nearby through district heating infrastructure. MGT with micro-CHP systems can also provide cooling through the use of absorption chillers that utilize heat as their energy source (i.e. Combined Cooling, Heating and Power). In this way, end-users from different sectors (including multi-family buildings, commercial, and industrial applications) become partners sharing responsibility for a greener and more sustainable energy supply. A micro-CHP system is also a controllable Distributed Generation (DG) solution that can empower consumers by enabling them to produce their own electricity and heat, taking control of their energy bills (i.e. becoming active participants in the energy market). Also, as viability of carbon capture and storage (CCS) solution for decarbonisation targets remains in doubt, micro-CHPs can play a leading role in this regard at the domestic level.

It is evident how such a system delivers important benefits to energy consumers as well as the wider energy system, in line with EU reaching its energy and climate objectives:

- Energy savings between 25%-44% (depending on the size of the MGT) compared to a traditional system of separate electricity and thermal energy generation,
- Savings on total energy costs for the end-user (as a function of electricity and heat savings),
- Improved efficiency of fuel use (better fuel utilization factor) (at least 25%[3]),
- High level of fuel flexibility,
- Use of alternative fuels, including renewables and syngas, to reduce natural gas consumption
- Reduced emissions (up to 33%[4]),
- Independence and security of power supply,
- Improving the energy performance of buildings,
- Supporting the electricity grid & helping the integration of intermittent renewables

[3] Compared to importing electricity from the grid and using boilers to generate heat

[4] According to models ran by Delta-ee, micro-CHPs technologies can reduce CO2 emissions by 17%-33% in a typical German family home compared to covering energy needs by an advanced condensing boiler and electricity from the grid. Retrieved from: http://bit.ly/1PmrmMc

4.2 Emission Reduction

Micro-CHP, in general, has the potential to reduce CO_2 emissions and reduces primary energy consumption compared to a conventional boiler with electricity drawn from the grid. Depending on different scenarios, micro-CHPs can save about 240-300 PJ (1 PJ is 31.6*106 m3 NG) primary energy per year (this is roughly 0.5-0.6% of the total energy used in the EU-27 in 2010). Based on that, greenhouse gasses can be reduced by 13-14 [Mton of CO2-eq/year] by using micro-CHP systems instead of gas boilers (this is equivalent to about 0.3% of the total EU-27 GHG emissions in 2010). Depending on the technology used, electrical efficiency of a micro-CHP unit ranges from 20% (for Rankine cycle and Stirling engine) up to about 60% (for solid oxide fuel cell). In terms of thermal efficiency, it can reach between 40% and 80% for different types of technologies.

A recent study from Delta – ee [33] shows that buildings account for 36% of CO_2 emissions in the EU. In this context, the MGT technology has been identified as one of the most suitable technology to lower GHG emissions. The use of clean fuel, such as natural gas, and the nature of the combustion allow MGTs to reach very low values polluting emissions. Current technology can reach a 59% reduction in carbon dioxide (CO_2) and 95% reduction in nitrogen oxide (NO_x) emissions compared to traditional systems. This is achievable thanks to the advanced combustion technology. Within MGT combustors, the chemical energy conversion of fuel into thermal power is much more controlled than other comparable technologies; the combustion chamber design is optimized for the control of NOx formation and emissions are one order of magnitude lower than in other combustion engines. The reduced temperatures of premixed flames inhibit the formation of nitrogen oxides while the excess of air instead restricts unburnt CO. Currently MGTs are inherently clean and do not require the use of abatement systems on the exhaust gas.

4.3 Financial Cost/Benefit Analysis

A financial cost/benefit analysis for a micro gas turbine system depends on the type of application, and even within the same application, there are a number of variables to be taken into consideration.

As part of the OMSoP project, the University of Seville (USE) has conducted an accurate cost analysis comparing data retrieved from the literature and data coming from OEMs partners contributing to this summary. It has to be noted that the analysis consider only manufacturing costs related to MGT and, as such, cost related to the other components as well as installation and profit of the company, have not been taken in consideration. The analysis reveals that manufacturing costs are strictly related to production rate for both data sources with a range between 200€-600€. Fig. 4.3 shows the relation between specific MGT cost and production rate

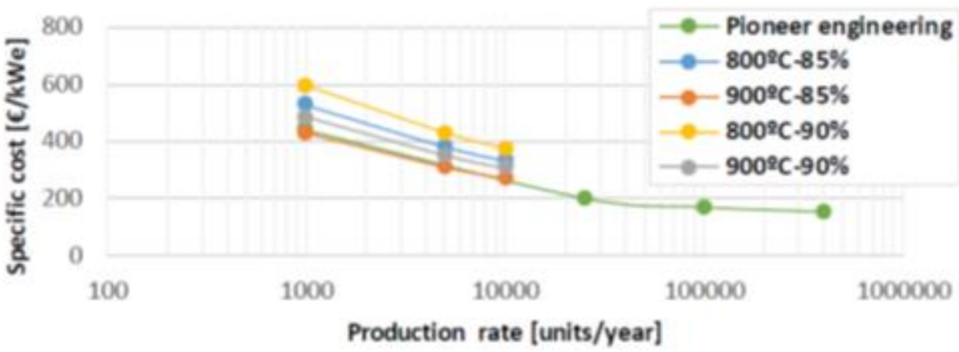


Figure 4-3: Specific manufacturing cost comparison

Another variable which influences the MGT cost is the electric output. Though the relation between cost and electric output is not linear, until a certain extend higher is the electric output, lower is the cost. The graph below shows this relation based on the data supplied by Compower for MGT units between 5-60kW.

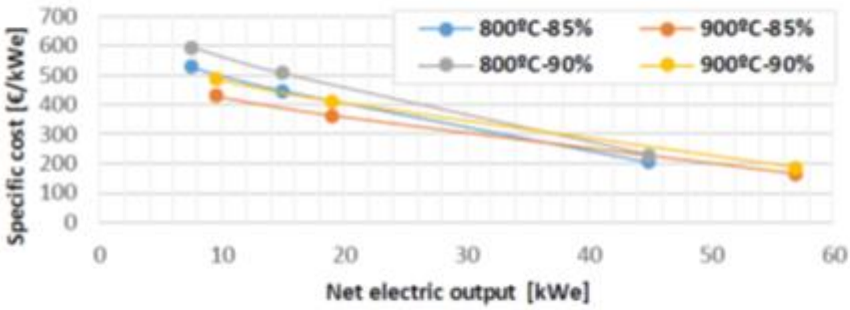


Figure 4-4: Specific manufacturing cost of the micro gas turbine vs. net electric output for 1000 units/year production rate

Considering the additional costs associated to the other components of the systems, like recuperator, power electronics, package, and the profit of the company, the MGT cost on the market range from 800€ to 2200€/kW. Adding heat recovery increases the cost by 100€ to 300€/kW.

When comes to maintenance, MGTs show a higher reliability comparing to the competing technologies. Currently most OEMs are targeting maintenance intervals of 5000-8000 hours with a lifetime of over 30000 hours.

The economic viability of MGT with micro-CHP is, first and foremost, dependent upon the size of the unit being appropriate for the building, the payback period of the technology and the Levelized Cost of Electricity (LCOE). In this application, it is necessary to consider the time profile of the energy consumptions requirements, in terms of heat/power ratio. An extremely important characteristic in energy consumption is represented not only by their averaged amount, but also by the irregularity degree with which they are requested during a reference time period (day, week, etc.). Indeed, the presence of strong irregularity in energy consumption could lead to a higher energy cost, and thus to a higher difficulty in identifying the reason of energy waste. A MGT CHP system is very flexible in terms of the ratio of heat to electricity production, hence being more adaptable to different users' needs.

Business cases developed by the MGT OEMs shows that a MGT with micro-CHP have a payback period of approximately 2-5 years, at an average LCOE of 0.04-0.07€/kWh.

Global energy efficiency of micro gas turbines is high if compared with other technologies, due to the use of waste heat for cogeneration; moreover, their compactness and high power-to-weight ratio make MGT suitable for small installation in real-estate and retail environment.

Technology	Power Output	Cost
Internal Combustion Engines	4kW – 6MW	600 – 4000 €/kW
Micro Gas Turbines	3kW – 400kW	900-2500 €/kW
Stirling Engine	1kW – 3kW	4000-8000 €/kW
Fuel Cells	1kW – 20kW	4500 – 30000 €/kW

Table 4-1: micro-CHP technologies comparison

4.4 Partnering with RES

Micro-CHP can play an important role in supporting renewables and meeting the challenges of the modern electricity grid. The technology is able to support renewables at the system level in Europe and can realise multiple benefits as a form of demand response, enabling householders and SMEs to change their electricity production and demand to suit grid conditions[5]. There is also evidence that micro-CHP technologies can be connected together and controlled remotely as part of virtual power plants, supporting the grid and avoiding further grid and infrastructure investments [34].

Another important contribution to increase the share of RES into heating and cooling sector may be given with future developments of hybrid systems. The Optimised Microturbine Solar Power System project has the aim to demonstrate the feasibility of the use of a MGT coupled with a CSP parabolic dish to provide energy needs for domestic and small commercial applications in the range of 5-30kWe. The system may be used in solar-only configuration or hybrid (with natural gas or biogas) in order to ensure the security of supply.

For a stand-alone, solar-only system, whose specifications are shown in table 4-2, the equipment costs would be in the range of 3014€/kWe to 3262€/kWe (table 4-3), without accounting for transportation and installation.

[5] Ecuity. The role of micro-CHP in a smart energy world. Retrieved from http://www.ecuity.com/wp-content/uploads/2013/03/The-role-of-micro-CHP-in-a-smart-energy-world.pdf

	TIT=800˚C / εrec = 85%		
	mGT mass flow rate [g/s]		
System design MGT SR SO SA	100	200	300
Net electric output [kWe]	7.5	15.4	23.5
Receiver - Net thermal power [kWt]	30.86	61.85	92.16
Receiver - Gross thermal power [kWt]	44.09	88.35	131.65
Dish - Gross solar energy [kWt]	48.99	98.17	146.28
Dish aperture area [m2]	61.24	122.71	182.85
Net system electric efficiency [%]	15.31%	15.69%	16.07%
Net mGT electric efficiency [%]	24.30%	24.90%	25.50%

Table 4-2: Summary of system specifications. Stand-alone, solar-only system with base-case technology (simple recuperative cycle)

	TIT=800˚C / εrec = 85%		
	mGT mass flow rate [g/s]		
Purchase Equipment Cost (PEC)	100	200	300
MGT [€]	4667	7934	10821
Solar receiver [€]	1040	1561	1796
Dish [€]	18386	36522	61030
BOP [€]	375	398	423
Total PEC [€]	**24468**	**46415**	**74071**
Spec PEC [€/kW]	**3262**	**3014**	**3152**

Table 4-3: Summary of purchase equipment cost (PEC) for the stand-alone, solar-only system with base-case technology (simple recuperative cycle)

For a stand-alone, hybrid system, the equipment costs would be in the range of 3047€/kWe to 3302€/kWe (table 4-4), without accounting for transportation and installation.

	TIT=800˚C / εrec = 85%		
	mGT mass flow rate [g/s]		
Purchase Equipment Cost (PEC)	100	200	300
MGT [€]	4964	8440	11681
Solar receiver [€]	1040	1561	1796
Dish [€]	18386	36522	61030
BOP [€]	375	398	423
Total PEC [€]	**24766**	**46921**	**74931**
Spec PEC [€/kW]	**3302**	**3047**	**3189**

Table 4-2: Summary of purchase equipment cost (PEC) for the stand-alone, hybrid system with base-case technology (simple recuperative cycle)

In the short term, such hybrid systems would allow a higher integration of RES into the grid by absorbing the fluctuations and by using natural gas, biogas, industry waste gas or landfill gas. In the long term, they would contribute to the achievements of the EU Climate and Energy targets set to decarbonise the energy system and to the full deployment of RES in the grid while ensuring security of energy supply thanks to the use of natural gas or other gas if needed.

An accurate literature review done by the ETN WG has brought to the identification of costs for based and hybrid MGT technology.

TECHNOLOGY	POWER OUTPUT	PRICE
NATURAL GAS	3 kW – 400 kW	900 – 2500 €/kW
OMSoP SOLAR	5 kW – 50 kW	3047 – 3302 €/kW
BIOGAS	3 kW – 250 kW	1000 – 2500 €/kW

Table 4-3: Cost comparison MGT-RES technologies[6]

[6] Data compared with the "Catalog of CHP Technology – Section 5. Technology Characterization – Microturbines, U.S. Enrvironmental Protection Agency Combined Heat and Power Partnership".

5 POLICY CONTEXT

5.1 EU POLICY FRAMEWORK

The priority of the European Commission is to develop its Energy Union Strategic Framework to ensure security of supply, affordability and sustainability of energy production. This strategy would facilitate the achievement of the goals of the 2050 low carbon economy Roadmap. The challenge of reducing greenhouse gas (GHG) emissions by at least 80% compared to 1990 levels in a secure and affordable way, would require an effective and balanced implementation of renewable energy sources (RES), increased energy efficiency improvements as well as carbon capture and storage.

Advancements in energy technology are vital if Europe's 2030 and 2050 targets are to be fulfilled. Combined Heat and Power (CHP) systems with RES (Concentrated Solar Power and Biomass) are technologies acknowledged by the European Commission in the Strategic Energy Technology (SET)-Plan. Adapting the current energy scenario into a truly sustainable one will require realizing the full potential for renewable energy sources to satisfy the heating and cooling demand. There will be equal efforts necessary from both generation and end-use sectors in order to achieve these ambitious targets for 2030.

MGT have a large potential to become a highly important power generation source for different applications, including when combined with CHP systems. In an EU context where the demand for heating power amounts to 46% of EU final energy use and where 40% of that energy consumption is related to buildings, micro gas turbine CHP systems can easily justify their place in the future energy sector.

According to the studies of the International Energy Agency, in 2012 just 43% of the energy input was converted to electricity with thermal power plant while co-generation power plant overall converts 61% of input energy into final electricity and heat. It is evident that one potential path towards a decarbonisation of the energy production consists in the share of electricity production using CHP, which accounts nowadays for 11% of the total power generation in Europe. Micro-CHP has gained interest in recent years due to its potential of providing efficient, clean and cost effective energy requirements for homes and small businesses. The main advantages of such systems are the provision of electrical and thermal energy wherever it is required, eliminating transmission losses and reducing the cost of energy infrastructures. The share of CHP in the total energy mix can and should be much higher, which will highly contribute to Europe’s climate and energy goals.

Biomass and Solar energy sources can further improve the decarbonisation of the energy production by integrating them with CHP systems. This integration would lead to a reduction of electricity production costs of biomass and solar based systems through a technology specific mix of decreasing investment and maintenance costs, increasing electric efficiency and availability, and reducing electricity price for the end-consumer compared to electricity from the grid due to instantaneous use.

The micro gas turbine technology is a promising technology that is finding its position in the market thanks to its flexibility of RES integration and to the lower costs compared to other technologies, as highlighted in the benefits/costs analysis in chapter 4. The current technology allows the distributed CHP to be adaptable with micro gas turbine (MGT) that could be integrated with RES (such as concentrated solar power (CSP) and biofuels) and would allow for CO_2 neutral power generation and cut down the cost of transport compared to centralised systems. However this poses challenges that are specific to the cycle configuration. Current technologies can handle specific types of biofuels and are commercially viable in large scale limiting their widespread deployment for distributed generation. The availability of suitable "CO_2 neutral fuel" as well as fuel flexibility (for improved reliability and availability) for small scale CHP are among the major challenges that needs to be addressed adequately to strengthen the interest for the technology. The availability of intelligent monitoring tools that can support non-expert end users is also an important challenge to address in order to enable the development for this technology.

5.2 Policy Recommendations

The decarbonisation of the future European energy system should guarantee the same level of reliability as the existing one. This can be achieved by deploying technologies already commercialised or in late development stage. According to most recent studies, the energy consumption in 2050 will grow of about 40% compared to today's need. It is evident that future demand can't be fulfilled without a mix of sources, which at the same time will enhance supply security.

The RES capacity's share will continue to grow and have a predominant position in the energy scenario, according to the priorities set by the European Commission in the SET-Plan. However, some of the main challenges towards the achievements of the EU 2050 targets are not sufficiently addressed. While focusing on the development of the future RES technologies and their implementation in the networks, there is a risk to leave on a side the issues of system and market integration, which will become a critical priority in the next years. High share of RES in the long term brings along extraordinary benefits, among which the reduced fuel costs and the reduction of greenhouse gas emissions. Nevertheless in the short term costs related to the operation of combined cycle power plants should be taken into consideration. It is necessary to make a balance of the entire energy system and adapt long term energy policies, which will encourage the deployment of RES and at the same time, make sure that also when these last ones are not available, we are going through the decarbonisation of the energy system.

The backup technologies for low load factor dispatchable capacity are yet uncertain. Currently the potential alternatives seem to be:

- Flexibilisation of Combine Cycle Power Plant
- New gas-fired plants
- Biomass/biogas fired plants
- Hydrogen-fueled plants
- Development of new energy storage technologies

All these options should be developed in parallel to the RES technologies, leaving some uncertainties on the market. Given the low Levelised Cost of Electricity and the emissions regulations in place, Utilities are not willing to invest further in existing or new assets for centralised power generation, which, according to the EU targets, should be dismantled in some years. The Utilities are then looking at Distributed Generation (DG), in which MGT can find its position. However there are still some policy issues limiting the development of DG technologies. Beside the security of supply, the connection to the distribution grids and networks are the main issues. How to incorporate potential public benefits in the tariffs has been largely discussed in Europe. To reduce the farm wastes, site owners are given incentives to install power generating equipment that utilises biomass or biogas.

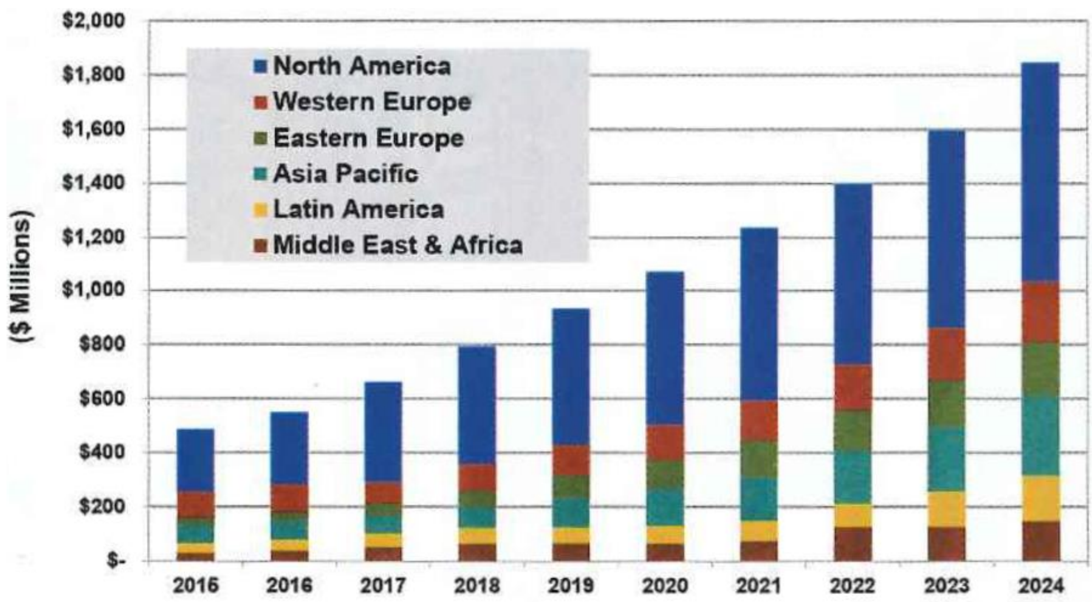
The next step to enhance the installation of DG technologies should also be to allow users to generate their own power and transmit the excess to the neighbours. Currently the same transaction costs for small power generation technologies owners and large power plants owner, thus limiting the competitiveness of small DG technologies.

6 Requirements on Deployment

Though MGT is a secure and established technology on the market, there are some barriers to be overcome in order to expand its position in the market. The ETN MGT Working Group has analysed and discussed the barriers for the deployment of MGTs as well the advantages it may bring to the energy market.

6.1 Investment and Market Barriers

According to the market analysis made by Navigant Research, the annual revenue from annual microturbine installation is expected to surpass $1 billion by 2020.



[7]

[7] ARTICLE Micro turbine boom predicted by 2020 – Navigant research

The use of MGTs in the oil & gas applications and in CHP and CCHP applications represent strong growth opportunities for a technology which is still in a niche market. Furthermore with the shift in Europe from centralised to decentralised power generation, an increased installation of MGTs is forecasted.

Utility rates and prices set by current energy utility providers, as well as uncertainty in natural gas prices, influence the development of MGT networks.

The table 6-1 summarises the main barriers and drivers for the deployment of MGT in the current energy market.

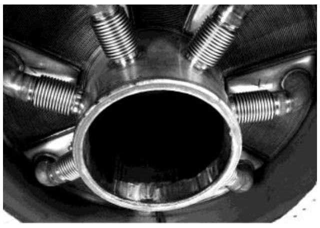
	Barriers	**Drivers**
Policy and regulations	• Economic efficiency • Lack of interconnection standards	• CHP and CCHP improving energy efficiency • Incentives to reduce emissions • Reduced fuel consumption in buildings
Market	• High gas prices • Low LCOE • Lack of connection between OEMs with distribution and marketing.	• Current electricity price volatility for industry sites.
Maintenance and installation	• Lack of customer expertise on the technology • Infrastructural issues related to the provision of the fuels needed	• Increased reliability and availability for energy sensitive applications •

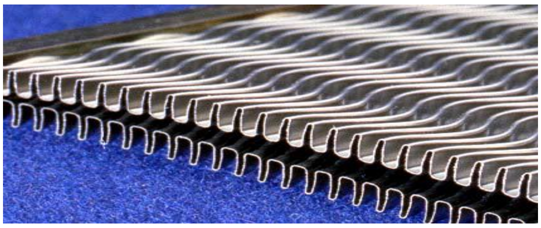
Table 6-1: Deployment of MGT in the current energy market

6.2 RECOMMENDATIONS & IMPORTANT AREA OF COOPERATION

To be able to run a microturbine system for power and heat supply with competitive cost attributes, a number of investments on microturbine systems' components have to be done. This chapter discuss in details the investments needed for each component.

6.2.1 Recuperator





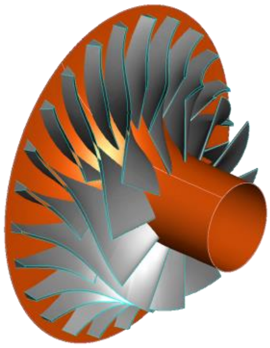
Biogas	• Increased effectiveness • Corrosion resistance • Clogging/fouling resistance • Lifetime
Biomass	• Increased effectiveness • Increased performance at lower temperature • Lower backpressure at higher mass flow • Lifetime
Solar	• Increased effectiveness • Lower backpressure at higher mass flow • Lifetime
Back-up RES	• Increased effectiveness • Cycles resistance lifetime

Table 6-2: MGT recuperator research activities

Investements in:

- R&D on special materials
- R&D on special design for higher effectiveness
- Special manufacturing process for lower production cost

6.2.2 Turbomachinery



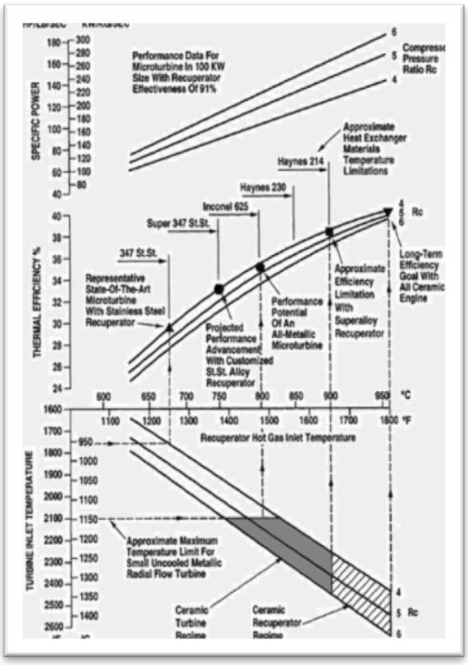
Biogas	• Increased TIT • Increased efficiency • Corrosion resistance • Wear resistance • Lifetime
Biomass	• Increased efficiency at lower speed • Increased performance at lower temperature • Wear resistance • Lifetime
Solar	• Increased efficiency • Increased performance at lower temperature • Wear resistance • Lifetime
Back-up RES	• Increased efficiency at part load

Table 6-3: MGT turbomachinery research activities

Investements in:

- R&D on special materials
- R&D on coatings
- R&D on special aero design for compressor and turbine
- Special manufacturing process for lower production cost

6.2.3 Combustion system



Biogas	• Higher TIT • Corrosion resistance • Lower emissions • Wear resistance • Lifetime
Biomass	• Wear resistance • Lifetime
Solar	• Higher temperature resistance • Corrosion resistance • Wear resistance • Lifetime
Back-up RES	• Lower emissions • Cycles resistance • Lifetime

Table 6-4: MGT combustion research activities

Investments in:

- R&D on special materials
- R&D on special design for lower emissions
- R&D on special coatings

6.2.4 Power electronics

Biogas	• Increased efficiency
Biomass	• Increased efficiency • Higher grid micro-interruption resistance
Solar	• Increased efficiency • Higher grid micro-interruption resistance
Back-up RES	• Increased efficiency • Power factor correction • Grid code compliance • Connection with energy storage • Off grid capability

Table 6-5: MGT power electronics research activities

Investments in:

- R&D on special materials for IGBTs
- R&D on special design
- R&D on special software
- Special manufacturing process for lower production cost

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