ETN
Global

DECENTRALISED ENERGY SYSTEMS: TOWARDS CARBON-NEUTRAL ENERGY SOLUTIONS FOR GAS TURBINES

ETN Global Report

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List of abbreviations

AFS	Axial Fuel Staging
Al	Aluminium
AM	Additive Manufacturing
BESS	Battery Energy Storage System
CCS	Carbon Capture And Storage
CCHP	Combined, Cooling, Heat, And Power
CHP	Combined Heat And Power
Cr	Chromium
CRS	Central Receiver System
CSP	Concentrated Solar Power
DES	Decentralised Energy Systems
DLE	Dry Low Emissions
DLN	Dry Low Nox
EB-PVD	Electron Beam Physical Vapour Deposition
GT-R	Gas Turbine Layout Recuperated
GT-ICR	Gas Turbine Layout Intercooled Recuperated
HCF	High Cycle Fatigue
HRSG	Heat Recovery Steam Generator
HTF	Heat Transfer Fluid
ICE	Internal Combustion Engines
LCOE	Levelized Cost Of Energy
LCOH	Levelized Cost Of Hydrogen
LCF	Low Cycle Fatigue
LHV	Low-Heating Value
MCFC	Molten Carbonate Fuel Cell
MHI	Mitsubishi Heavy Industries
MILD	Moderate Or Intense Low-Oxygen Dilution
NG	Natural Gas
OEM	Original Equipment Manufacturer
P2P-ESS	Power-To-Power Energy Storage System
PURPA	Public Utilities Regulatory Policies Act
PVs	Photovoltaics
RES	Renewable Energy Sources
RQL	Rich-Burn, Quick-Quench And Lean-Burn
SOFC	Solid Oxide Fuel Cell
TBC	Thermal Barrier Coating
TES	Thermal Energy Storage
UAV	Unmanned Aerial Vehicle
ULN	Ultra Low Nox

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Highlights

1. As compared to traditional centralised heat and power units, DES offer several advantages including modularity, the possibility to exploit waste heat avoiding energy transmission losses and reducing energy distribution costs.

2. Despite all these advantages, policy and regulatory barriers impede the development of distributed generation (DG) technologies, hindering the progress of DES.

3. Emerging market opportunities such as smart grids and microgrids, as well as potential for services like grid stability, reliability, load balance and power quality present avenues for growth in the DES sector.

4. Among the technologies, gas turbines are increasingly utilised for different DES applications. Gas turbines are economically competitive for applications between 1 MW and 10 MW and prevalent in installations exceeding 10 MW. Nevertheless, they lose competitiveness to reciprocating engines in smaller capacity ranges below 1 MW, due to higher capital cost and lower fuel conversion efficiency.

5. Technological advancements in fuel cells make the market even more competitive for gas turbines in DES, particularly if fuel cell prices significantly decrease. Despite this, gas turbines remain more competitive overall.

6. Critical challenges for small gas turbines such as micro gas turbines in DES include enhancing performance and improving part-load operations. This involves increasing turbine inlet temperature and enhancing performance of recuperators with a focus on heat exchange and materials.

7. Gas turbines demonstrate great potential as dispatchable and fuel-flexible prime movers for DES, enabling the utilisation of renewable fuels such as syngas, biogas, and hydrogen.

8. Promising applications for gas turbines in DES include integrating thermal energy storage and hybrid configurations, enhancing their versatility and efficiency.

9. Continued research and development efforts are essential to drive the growth of DES and facilitate the transition to sustainable energy systems.

Vision

High share of renewable energy sources (RES) has already begun transforming the energy sector. In a scenario of increasing variable energy sources the daily, weekly, and seasonal flexibility is set to grow dramatically [1]. To meet the requirements while accomplishing the ambitious goals on decarbonisation, the system requires a mix of decentralised components, such as demand response and distributed generation, alongside the traditional centralised generation. In a decentralised era, small gas turbines are technically attractive options that can play a key role in providing the required flexibility, security of supply and stabilising the power grid, by providing clean and dispatchable heat and power to residential, commercial, and industrial end-users.

Micro gas turbines can be used to provide heat and power to smaller consumers (due to their fuel flexibility), whereas larger gas turbines (in the range from 2 MWe to 20 MWe) are used in large scale industrial applications.

DES provide the end-users with significant advantages, such as the opportunity of utilising renewable energy sources without or at least minimizing transmission and distribution losses. Reducing the primary energy consumption by exploiting the efficiency potential of gas turbines, as well as achieving emission reduction targets are additional benefits. DES are therefore pivotal in meeting the pillars of the energy trilemma, which stresses the principles of affordability, security, and climate neutrality, and hence align with the strictest requirements long-term EU transition policies towards 2030, 2040, and 2050.

1. DES: a state-of-the art

DES are located close to the consumption nodes, on the end-user side of the network and therefore connected to the distribution grid. Conversely, for the centralised generation (the current scenario) large, centralised plants are located far from the consumers and in most cases connected to the transmission grid.

DES bring the advantage of modularity and location flexibility, the possibility to exploit waste heat and positively contribute to grid stability, reliability, load balance and power quality. In particular, being close to the consumption nodes avoids energy transmission losses and reduces distribution costs and energy losses compared to centralised generation. For these reasons, their contribution might be relevant to achieve the ambitious objectives of the European Union, whose Green Deal plans to make Europe the first climate-neutral region in the world by 2050. On the other hand, DES could feature higher capital and energy cost and may depend on the availability of local resources (e.g., locally produced fuels).

DES comprise several different subsystems and technologies operating in conjunction. These include:

- Internal and external connections allow the flow of energy (e.g., power, heat, and fuel) and information within the decentralised system and between the system and the outer grid. Exchanging information with energy is increasingly paramount in modern energy systems and smart grids.

- Renewable energy sources (RES) have a significant role in achieving the 2030 and 2050 objectives. They depend on clean natural resources. However, they introduce unpredictability and uncontrollability.

- Energy Storage is often needed to overcome the challenges associated with the unpredictable renewable generation and the fluctuating energy demand. It includes short-term and seasonal storage.

- Core generators, together with RES and energy storage, are often necessary to provide secure and reliable energy and ancillary services. The commercial technologies that can provide this service are gas turbines, reciprocating internal combustion engines (ICEs), and fuel cells. In particular, this report will focus on gas turbine technologies and their integration into DES.

The goal of this report is to provide potential users with an overview of integrating gas turbine technologies in DES. With this work, the DES Working Group of ETN Global aims at stressing the prominent role of gas turbines in future energy scenarios. Effectively, gas turbines are based on a reliable, and efficient technology needed to provide energy flexibility and security in a fast-changing framework. The shift from a centralised to a more decentralised paradigm, dominated by unpredictable renewables, would arguably need such a consolidated technology. The great versatility of gas turbine technology makes them appropriate for a wide range of conventional and unconventional applications. Finally, as a fuel-flexible technology, gas turbines can significantly sustain and enable the transition to clean fuels like low-carbon hydrogen. Effectively, several commercial gas turbines are already able to run with an increasing proportion of hydrogen blends.

This report is divided into three chapters. Chapter 1 presents the DES state-of-the-art, including DES definition and primary applications, DES market forecasts and trends, technological challenges, and regulatory frameworks. Then, Chapter 2 describes the integration of gas turbine technologies into DES, including some future conventional and unconventional applications. Finally, Chapter 3 summarises the findings of previous chapters and suggests future directions.

1.1. DES definition & primary applications

DES definition and role of gas turbines and micro gas turbines

Decentralized energy systems are characterized by energy generated in the distribution grid (i.e., off the main transmission grid) closely located to the end-user rather than at a centralized large plant elsewhere and transmitted through the national grid. Decentralized energy systems involve using a variety of smaller power generation plants and storage units that can be grid connected to provide energy. They usually integrate several energy vectors, at least electricity and thermal energy, but also to an increasing extend the gas grid, as well as interfacing with other relevant sectors such as industry and transport. Decentralized energy systems might be island systems in some cases but are expected to be connected to and interacting with other neighbouring systems.

The size of decentralized energy systems can vary between several kW (house-level) up to tens of MW in the case of energy systems on the district level. When considering gas turbine size, it is expected to cover in most cases the range of micro gas turbines up to industrial gas turbines and sometimes even larger ones. The integration of the GT with the system in terms of interaction with the electrical and thermal systems on the demand side as well as with the fuel and feedstock system on the "fuel" side is to be considered. It can be expected that the relative changes on the supply side and the demand side are increasing with the decreasing size of the system and the "averaging" effect of many components with different profiles in generation or demand spread over a large area is reduced.

The role of micro gas turbines and gas turbine in DES can be separated between today's applications and those expected to be in future energy systems.

- Today micro gas turbines and gas turbines are in most cases used as CHP units and an important contributor to provide power and heat. The operational profiles range from base load applications to flexible operating units to cover local demand profiles and / or in connection with other energy generating units in the system.

- Future energy systems are expected to be predominantly based on a large share of renewables, most of them fluctuating given the high maturity level of photovoltaics (PVs) and wind and their comparatively low cost. In such scenarios the expected role of micro gas turbines and gas turbines is for backup and peaking power. It also needs to be expected that the fuel / heat source might be diverse depending on local boundary conditions and with fuel / heat being to an increasing extend based on renewable sources (e.g., green hydrogen, green ammonia, bio-based fuel, and e-fuels). The sketch of decentralized energy system of the ROBINSON project *(Figure 1)* might serve as an example.

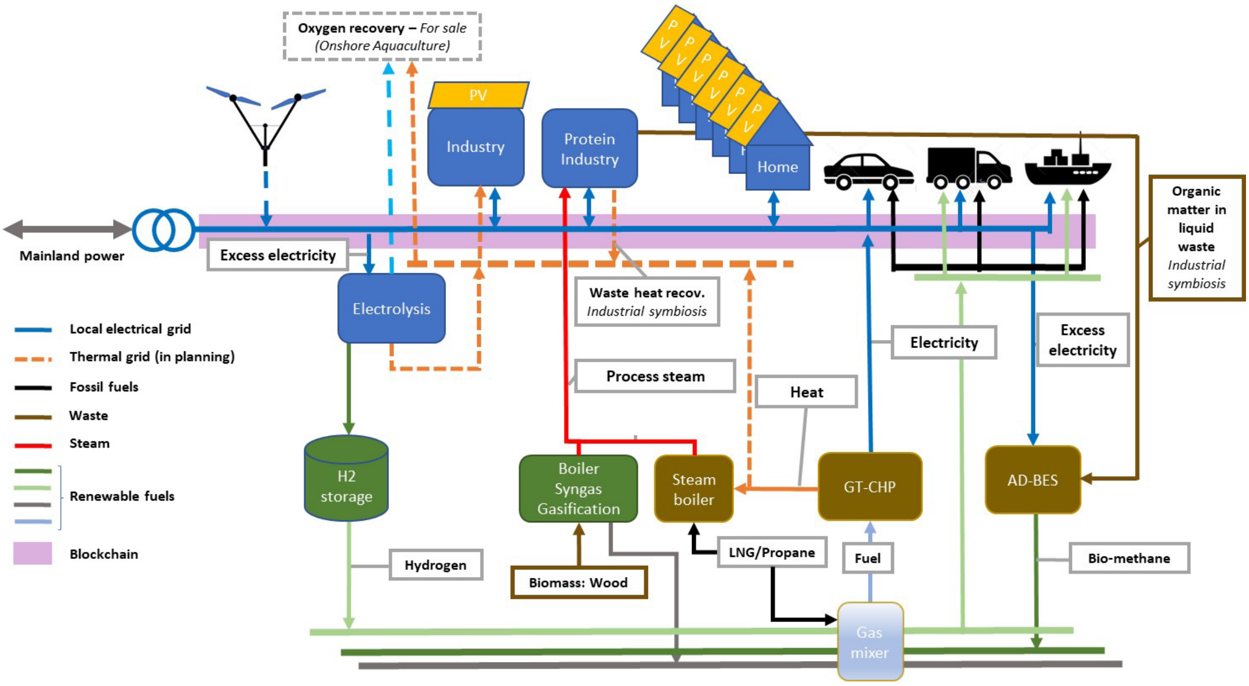

Figure 1: ROBINSON – an example of a decentralized energy system with a gas turbine-CHP

- It is furthermore a possibility that the integration of micro gas turbines and gas turbines in industrial processes gain interest in connection with energy efficiency improvement. In these cases, a closer coupling of the industrial process and the power generation process might require different operational strategies (start-up, shut-down, and transients) and a modification of the gas turbines. An example is the integration of gas turbines and fuel cells which was evaluated already around 2000 [2].

Micro gas turbines and gas turbines thermodynamic cycle

The thermodynamic cycle behind the gas turbines is named Brayton cycle. The ideal cycle consists of 4 main processes:

1. Adiabatic compression.
2. Constant pressure fuel combustion.
3. Adiabatic expansion.
4. Cool the air at constant pressure back to its initial conditions.

The Brayton cycle can take the form of an open (1-2-3-1) or a closed cycle (1-2-3-4-1) *(Figure 2)*. The working fluid is renovated after every cycle in the former whereas it is recirculated in the latter. In addition, the internal combustion chamber is replaced by a heat exchanger when it is a closed cycle. This section focuses on the open cycle since it is the main subject of the work. Some variation of the cycle, namely, regenerative, regenerative/intercooling and regenerative/intercooling/reheating are described in the section.

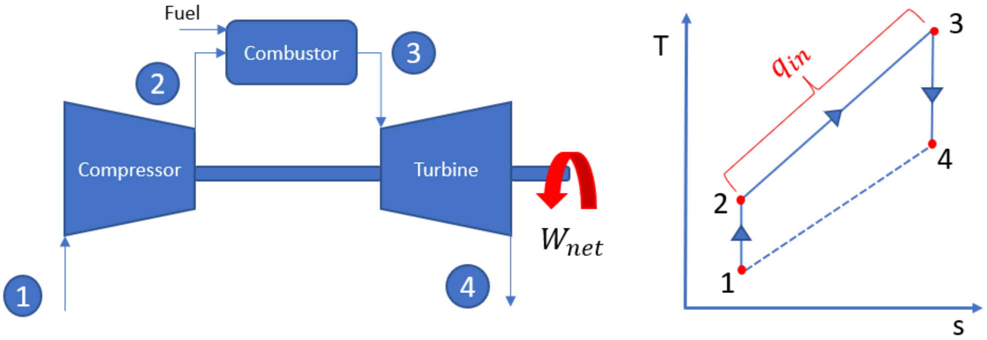

Figure 2. Sketch of the simple Brayton cycle and the T-s diagram.

Figure 2 also shows the corresponding thermodynamic states. Both the compressor and turbine are of dynamic types, either axial or centrifugal configurations. Both devices are connected in the same shaft such that the turbine drives both the generator and the compressor. The combustion chamber usually uses a Dry Low Emission (DLE) configuration. ETN Global report on "Micro Gas Turbine Technology: Research and Development for European Collaboration" details the configuration and the latest development trends of the different components that form the micro gas turbine.

The thermal efficiency of the Brayton cycle can be expressed as the ratio of the work done by it to the heat supplied to it. Work done by the cycle is expressed as the difference between the turbine work and the compressor work. Heat supplied is a function of the fuel mass flow and low heating value (LHV). *Equation (1)* defines the thermal efficiency of the Brayton cycle.

$$\eta_{th} = \frac{Network}{Heat\ in\ (q_{in})} = \frac{w_{tur}\text{-}w_{comp}}{m_{fuel}\cdot LHV} = \frac{(h_3\text{-}h_4)\text{-}(h_2\text{-}h_1)}{m_{fuel}\cdot LHV} \quad (1)$$

Enthalpy is a function of temperature (T) and pressure (p). Thus, the thermal efficiency is maximised by maximising/minimising the temperature and pressure at state 3/1. In the case of gas turbines, the cycle maximum temperature is limited by the material heat resistance and cooling techniques, and the maximum pressure is optimised. The minimum pressure and temperature are restricted to ambient conditions.

Simple open cycles are widely used in the order of MW scale gas turbines due to the feasibility of using axial compression with high-pressure ratios as well as advanced cooling techniques. On the contrary, when a smaller scale (< 500 kW) of power is considered, the working fluid volume flow is highly reduced, hence, centrifugal compressors and radial turbines are adopted [3]. In addition, the efficiency of turbomachinery decreases as the gas turbines reduce in size, resulting in a decline in engine performance [4]. Nevertheless, the main constraint of this configuration comes from the fact the maximum pressure of the cycle is constrained by the maximum pressure ratio delivered by a single stage centrifugal compressor stage, which is around 3.5-5:1. In addition, the non-ability of cooling in centrifugal turbine blades limits the maximum temperature of the cycle to the maximum heat resistance of the material. These two effects highly downgrade the thermal efficiency of the Brayton cycle. The thermal efficiency of a simple Brayton cycle only depends on the pressure ratio for ideal gas and isentropic compression and expansion as shown in a few paragraphs below. Thus, since the pressure ratio is reduced from around 20 to 3.5, the thermal efficiency goes down from around 57% to 30%.

Because of the latter, the regenerative Brayton cycle is used instead. In this case, a heat exchanger is used to exchange heat between the compressor exit flow and the exhaust gas streams. *Figure 3* shows the sketch of the regenerative Brayton cycle as well as the thermodynamic states. The maximum regenerative heat that can be recovered from the exhaust gas is (2,5') but due to inefficiencies during the heat transfer, the total heat transfer would be (2,5). Therefore, q_{in} is lower in the case of the regenerative Brayton cycle than in the case of the simple Brayton cycle. The question that arises is when to adopt the regenerative Brayton cycle instead of the simple Brayton cycle.

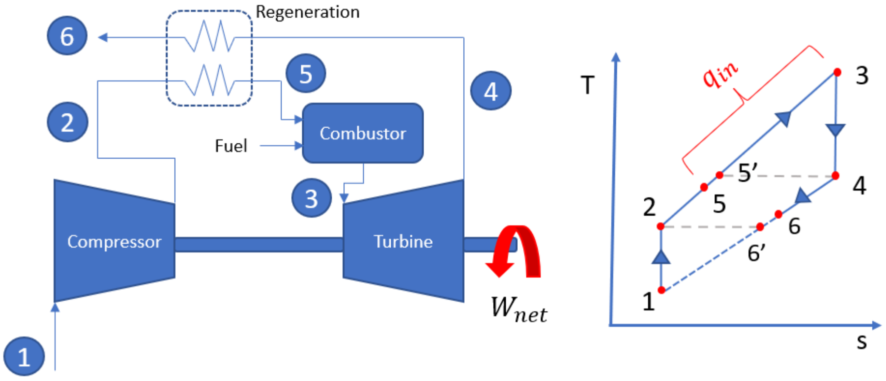

Figure 3. Sketch of the regenerative Brayton cycle and the T-s diagram.

In order to assess when to adopt the simple or regenerative Brayton cycle, *Eq. (1)* can be expressed in terms of the thermodynamic properties of temperature (T) and pressure (p) for each state assuming an ideal cycle, compression and expansion as polytropic processes, and that the mass flow through the compressor and turbine are the same. *Equation (2) and (3)* represents the thermal efficiency for the simple and regenerative Brayton cycle, respectively. Thus, thermal efficiency is a function of the pressure ratio (r) and polytropic coefficient (k) for the simple Brayton cycle and as a function also of the temperature ratio (T1/T3) for the regenerative Brayton cycle. Next, the thermal efficiency for both cycle configurations can be plotted as a function of the previous thermodynamic parameters. *Figure 4* suggests that regeneration is most effective at lower pressure ratios and low minimum-to-maximum temperature ratios. This is so because the higher the pressure ratio, the lower the regenerative potential as compression outlet temperature is higher.

$$\eta_{th}=1-r^{(1-k)/k} \quad \text{– Simple Brayton cycle} \qquad (2)$$

$$\eta_{th}=1-\frac{T_1}{T_3}r^{(1-k)/k} \quad \text{– Regenerative Brayton cycle} \qquad (3)$$

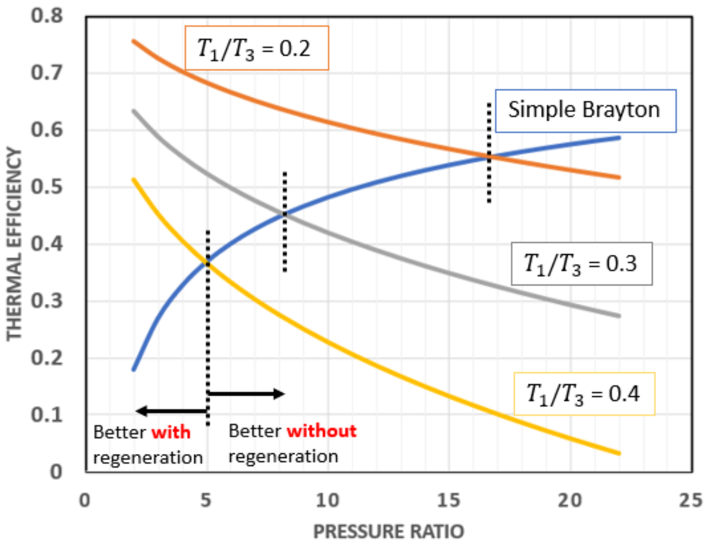

Figure 4. Evaluation of thermal efficiency of simple vs regenerative Brayton cycle.

However, the recuperative Brayton cycle can be upgraded to increase thermal efficiency. If only the thermodynamic cycle layout is considered, these upgrades could come by improving the compression efficiency and including reheating. These two factors are integrated into the so-called regenerative-intercooling-reheating Brayton cycle, displayed in *Figure 5*.

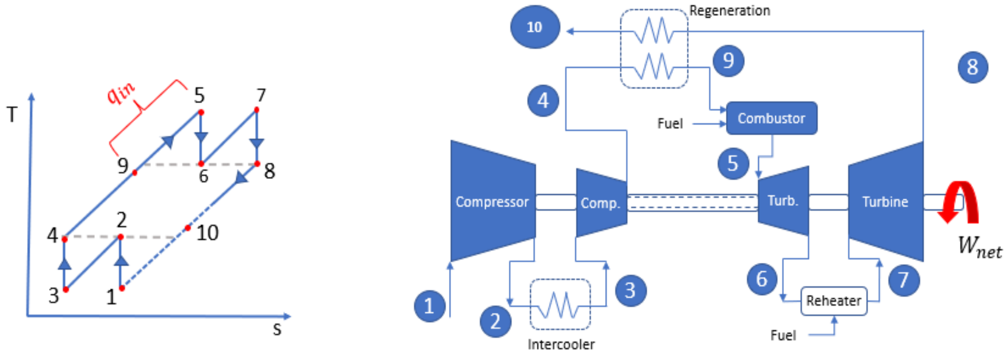

Figure 5. Sketch of regenerative, intercooling, and reheating Brayton cycle and T-s diagram.

An important part that was lacking from the previous analysis was the use of the high-grade heat that is available in the stream at the outlet of the Brayton cycle. The stream at high temperature can be directly used in any industrial process or redirected to a Heat Recovery Steam Generator (HRSG) where steam is produced to satisfy any industrial process or to be used for residential heating. Hence, the heat capacity of the stream (mass flow and temperature) at the exit of the Brayton cycle will determine the potential application that can use this source of waste heat. When regeneration is in place, the outlet temperature of the stream is highly reduced due to the regeneration process. Thus, Combined Heat and Power (CHP) is the term used to describe the physical power plant in which the waste heat created from the engine operation is captured and utilized for things such as heating water, cleaning, steam, and manufacturing.

Therefore, when considering a CHP application, the global efficiency of the plant can be calculated as follows:

$$\eta = \frac{E + H_{CHP}}{F_{CC}}$$

Where E is the total power produced by the CHP unit, H_{CHP} is the useful heat produced by the H_{CHP} unit and F_{CC} is the fuel consumed by the CHP unit.

Apart from the global efficiency of the CHP unit, the directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 *(European Comission and the Council, 2004)* on the promotion of cogeneration based on a useful heat demand in the internal energy market specifies the cogeneration technologies covered, the calculation of electricity from cogeneration, a methodology for determining the efficiency of the cogeneration process and a criteria for analysis of national potentials for high-efficiency cogeneration [5].

1.2. DES market forecasts and trends

DES, per definition, usually require drastically lower installed power than centralised systems. For this reason, as discussed later in this section, the gas turbine technologies primarily utilised in DES in terms of installed units are small and micro gas turbines.

Micro gas turbines are often considered a different technology and market segment. They are defined as units below 400kW. They mainly feature radial/centrifugal turbomachinery and low turbine inlet temperature and pressure ratio. The majority of commercial products are single-shaft, recuperated units. However, some multi-spool, recuperated-intercooled microturbines were studied and commercialised during the last decade [6]. Aeroderivative and heavy-duty gas turbines mostly feature axial turbomachinery and very high turbine inlet temperature and pressure ratios. Small gas turbines blend from micro turbines to larger aero-derivative and heavy-duty turbines, sharing some features. Aeroderivative gas turbines, as the name says, are aero engines adapted for power and heat generation. They usually present higher performance and compactness than heavy-duty gas turbines, although they tend to have higher capital costs and lower maintainability. Heavy duty covers the highest spectrum of the rated power. They range above 75 MW, thus, being very suitable for centralised generation and relatively uncommon in decentralised applications.

The global micro gas turbines market estimates are uncertain and can range between USD 100 and 200 million [7]. The gas turbine market, however, is estimated to range between 19 and 22 billion; it is hard to establish which proportion corresponds to DES. As a frame of comparison, the reciprocating ICE energy application market is valued at around USD 20 billion.

The first gas turbine plant was installed in 1938, whereas the first commercial microturbines were released in the late '90s. Micro gas turbines were initially quite successful and started becoming popular in the first decade of the 2000s. Nevertheless, their sales had a sharp drop due to their lack of competitiveness against reciprocating engines [8] and a decreasing interest in distributed generation partially caused by a surge in gas prices.

Figure 6 shows a similar pattern for the US CHP installations below 100MW. For the micro size (below 1MW), reciprocating engines are the most widespread technology, followed at a distance by microturbines and fuel cells. Between 1MW and 10MW, small gas turbine capacity is about 30% less than reciprocating engines. Finally, gas turbines are the most adopted technology for installation between 10MW and 100MW (mid-size). According to the same database, the average installed capacity is 320kW for microturbines, 700kW for fuel cells, 1MW for reciprocating engines and 24MW for gas turbines. In terms of number installations, micro-size applications count the most (2627), followed by small (986) and mid-size (218). The US CHP database only count 21 installations higher than 100MW.

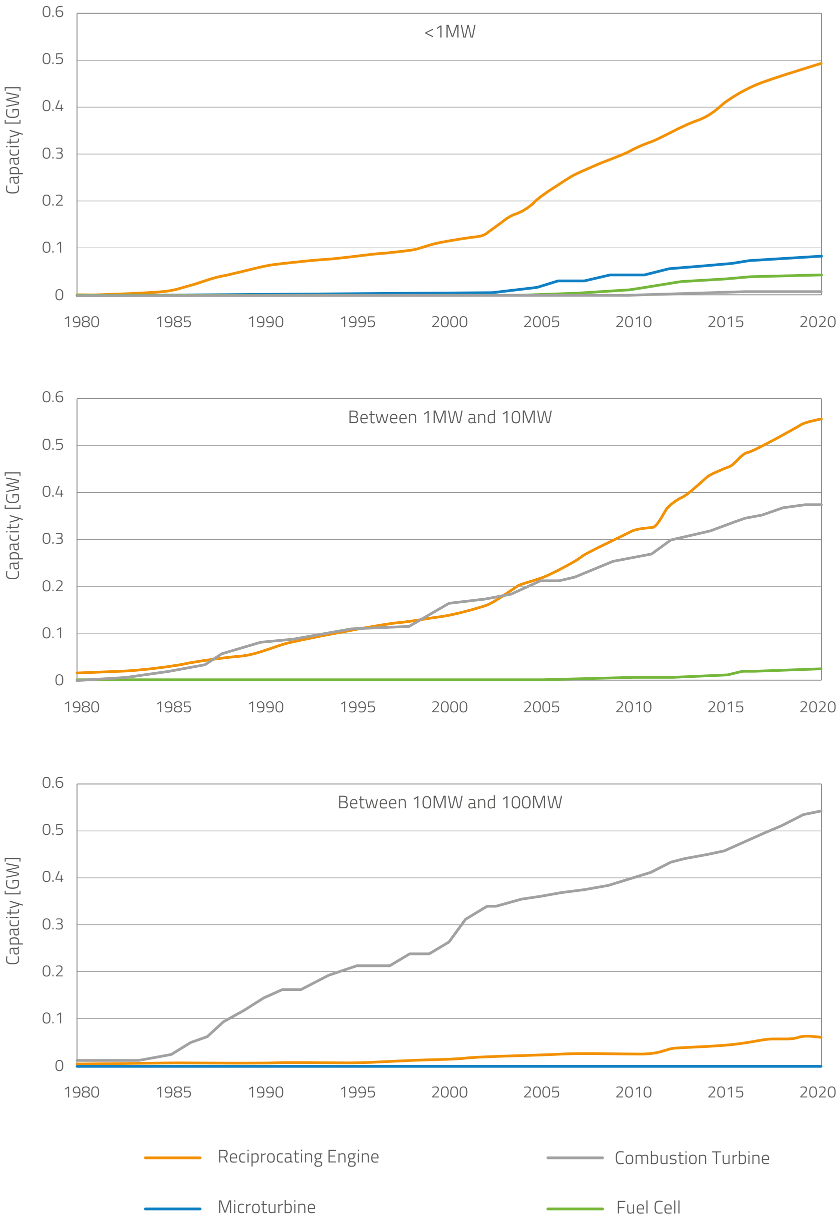

Figure 6: US CHP cumulative installations (capacity) below 100MWW listed for different prime movers. Source ICF CHP database 2022 [9].

Current and emerging applications for small gas turbine systems

Micro and small – and partially aeroderivative – gas turbines tend to compete with reciprocating engines and fuel cells. Due to their larger capacity, heavy duty gas turbines tend to compete with other technologies like steam turbines.

Table 1 presents the technical and economic comparison of some of these technologies relevant for decentralised applications.

	Gas Turbines			ICEs	FCs
	Micro Gas Turbines & small Gas Turbines	Aero derivative	Heavy Duty		
Capital cost	Mid	Mid	Mid	Low	High
Maintenance Cost	Low	Low	Low	Mid	High
Electric Efficiency	Low-Mid*	High	Mid	Mid-High	High
Waste Heat Grade	Mid-High	Mid -High	Mid-High	Low-Mid	Low-High**
Heat to Power Ratio	High	Low-Mid	High	Low-Mid	Low-Mid
Emissions	Low	Low	Low	High	None
Mechanical power	Low Torque	Mid Torque	High Torque	High Torque	None
Fuel Flexibility	Mid-high	Mid-high	High	Mid-high	Low
Load Responsiveness	High	Mid-High	Low	High	Low-high**
Availability	>95%	>95%	>95%	85%-95%	>95%

Table 1: Technical and economic comparison of prime movers for decentralised applications.

* Refers to simple and recuperated cycle turbines. Commercial recuperated-intercooled micro gas turbine can achieve over 40% efficiency.

** Depends on fuel cell type

Considering the remarks in Section 1 and *Table 1* reports, gas turbines established networks in specific niche markets. In particular, gas turbines leverage the fact that the whole heat is contained in the exhaust at medium-to-high temperature. Moreover, the high O_2 content allows downstream duct firing to increase the heat grade or the heat ratio [10].

Their capability of burning low LHV fuel with fluctuating composition makes them suitable for waste fuel applications. Moreover, their large maintenance intervals and high reliability make them suitable for remote applications. The current market niches are:

- Cogeneration:
  - Applications with mid/high-grade heat (mainly industrial) or high heat-to-power ratio (industrial, commercial and some new products entered the residential sector).

- Waste fuel:
  - Oil and Gas: off-shore flare.
  - Sewage and Biofuels with low and variable LHV.

- Primary generation/continuous power:
  - Remote applications, e.g., telecom towers.

Conversely, micro and small gas turbines never managed to establish themself for transport applications. Due to the low torque gas turbines are not very suitable for delivering mechanical power. Hence, they are not apt to be used as direct drives. Several attempts have been made to use them as range extenders in hybrid applications, but they have yet to be successful. Besides a few cases, the automotive industry never deployed range extenders in mass-produced vehicles and standard ICEs were used in hybrid cars. Nevertheless, a new generation of range extenders could fit into the growing electric vehicle market. Currently, some companies are looking into this new market opening and developing range extenders for electric vehicle applications.

Hybrid aerospace propulsion represents another new potential application. Some new companies (reference) are developing small gas turbines for hybrid aerospace propulsion for small aircraft and unmanned aerial vehicle (UAV). In this case, the leverage on the small size of the gas turbines drives to enter this segment.

Larger aero gas turbines are the established technology for commercial and military aviation. Additionally, large gas turbines are used as direct, or hybrid drives for naval propulsion. Nonetheless, the fuel consumption of gas turbines tends to be lower than Diesel engines of equivalent capacity [11]. Historically, the naval segment was never successfully targeted by micro and small gas turbines due their low torque and higher capital and fuel costs, with few exceptions [12].

Gas turbine role in a future DES

The **hydrogen** economy and value chain are gaining momentum, and hydrogen as a fuel is expected to have central importance in a low-carbon economy. Currently, the possibility of using hydrogen as a fuel for small gas turbines is under research. Some promising experiments show the potential hydrogen-gas turbines in an existing microturbine - changing fuel system and combustor - with no penalty in efficiency and little increase in NO_x emissions.

DES with on-site production of hydrogen could provide reliable and carbon free energy to rural communities, remote locations and industries. In Power to Hydrogen to Power applications, RES technologies provide power to the grid. Surplus power is stored into hydrogen and used when needed. This may include short-time storage for backup power as well as seasonal storage. The Levelised Cost of Hydrogen (LCOH) will depend mostly on the RES and electrolyser cost. With the current capital cost of PV, Wind, Electrolyser and Storage [13] *(Table 2)*, the ETN Global LCOH calculator [14] projects a LCOH around 7-10 €/kg for decentralised applications.

Item	Capital cost		O&M cost	
Wind turbine	1695	€/kW	51	€/kW/year
PV	1000	€/kW	9	€/kW/year
Electrolyzer	1500	€/kW	20	€/kW/year
Water			4.9	€/m³
HP vessel	70	€/Nm³		
Compressor	4000	€/kW	240	€/kW/year

Table 2: Capital and O&M cost for a Decentralised Hydrogen backup Energy System

The role of microturbines in hydrogen will largely depend on how the hydrogen market evolves. There, the competitiveness of micro gas turbines against ICEs and FC will be the key. For load-following applications with such expensive fuel having good maximum and part load efficiency is crucial to achieve an acceptable economic competitiveness. High-efficiency gas turbines – like intercooled-recuperated micro gas turbines and aeroderivative gas turbines – could target many segments where the lower gas turbines efficiency is a limitation. Indeed, the lower fuel and maintenance cost and the superior availability could be a compelling set of features for applications that require reliable power and contained O&M costs.

The predicted dismission of reciprocating engines due to more stringent regulations on emission for automotive applications could affect their economy of scale. Possibly, ICEs will still be strong in their heritage and keep their hold on the market. Their capability to remain cost competitive and run on low-carbon fuel would likely affect their possibility of survival in the long term. In addition, fuel cell is currently not competitive due to the extremely high equipment cost and short equipment life [15].

The long maintenance intervals and high reliability of micro gas turbines could make them suitable for critical **Stand-by power** applications that require reliable and fast-responding backup power, like data centres. Sometimes, several redundant units are present to overcome failures in emergency start-ups. The higher reliability of microturbines can bridge the capital cost gap with other technologies by limiting the need for redundant units.

Emerging economies can be an excellent opportunity for expanding the DG and microturbines market, despite the several challenges involved [16]. In particular, microturbines can reduce the investment in creating or improving the electrical grid in remote locations with no access to the grid or areas with a very unreliable and unstable grid. For instance, according to the International Energy Agency, Africa's energy will rise two times faster than the global average, with NG driving the industrial growth in the continent [17]. Moreover, mini-grids and stand-alone generation are likely the least cost options for nearly a third of the population gaining access to electricity by 2030.

Worldwide, **smart grids** and **microgrids** could be one relevant opportunity for microturbines. Their adoption can help guarantee the flexibility and reliability of power and heat in conjunction with RES and energy storage. EU projects like ROBINSON H2020 [18], funded by the EC Horizon2020 with the coordination of ETN Global and involving many institutions along with Aurelia Turbines – an original equipment manufacturer (OEM) – aims to study the impact of such systems.

Some potential is still present for micro gas turbines as **range extenders** for heavy transports (from 100kW to 400kW). The micro gas turbines industry tried several to "create" this new market segment. Currently, with the increasing adoption of electric and hydrogen vehicles -and their range limitations- this application may come back to interest. The drivers are a combination of compactness and reliability against fuel economy (range). Some companies like UAV turbines, Sentient Blue, and Turbotech are developing similar products for micro and small aircraft applications.

1.3. Technologies challenges for DES applications, limits, and role in the energy system

Turbomachinery

The turbomachinery components compressor and turbine are usually radial, a simple, cost-effective and efficient technology 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 since 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. These units are more complex and for higher power machines, while radial turbomachinery has better efficiencies for powers up to 100 kW.

Micro gas turbines efficiency is a key factor for competitiveness in relation to alternative prime movers for most if not all application areas. Although the 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. Therefore, an effort should be made to enhance its performance. This target can be obtained by increasing the firing temperature to improve Brayton cycle thermodynamic efficiency or by means of an integrated and optimised design of micro gas turbine components (centrifugal compressor, radial inflow turbine, recuperator etc). Both these approaches are objects of research even though they have different impacts on the 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, while leading to important performance enhancements.

1.4. Materials

The gas turbine materials for DES applications fall into the following categories:

- Materials used for cold section components (i.e., compressor)
- Materials used for hot section components (i.e., combustion and turbine)
- Materials used for the disc and rotor, and
- Materials used for microturbines.

Materials for the cold section

For the compressor, where a mix of strength, high cycle fatigue (HCF) resistance and corrosion resistance are the important requirements, a mix of martensitic stainless-steel alloys containing 12-13% Cr (including some precipitation hardened grades such as 15-5PH alloy) are routinely used for the blading (both rotating and stationary). Titanium alloys, with combined HCF and corrosion resistance, are occasionally used for the front row for a few compressor types. IN718 is used at the back of compressors with a high discharge temperature (>500 °C).

The martensitic stainless-steel aerofoils are normally coated with a corrosion resistant coating. This may be a sacrificial slurry coating ~30-50 microns thick, or a corrosion-erosion resistant titanium nitride coating, ~5-10 microns thick, applied by vapour deposition. These coatings are expected to provide some anti-fouling characteristics. Additionally, the contact faces of the blade root might be coated with anti-fretting coatings (such as copper-nickel-indium). The traditional slurry coating contains some hexavalent chromium (a substance banned under EU regulation 1907/2006). A chrome-free version of the coating has recently been introduced by some manufacturers.

Hot section materials

Combustion materials

Ni-based superalloy sheet metals with good formability and oxidation resistance (such as IN-617, Hastalloy X, Nimonic 75, Nimonic 263 and Hayness 230) are used for manufacturing the combustion liners and transition ducts. The combustion materials are expected to reach an operational life of 24,000 hours to 48,000 hours, subject to the metal temperature not exceeding ~860°C during operation. To control the metal temperature, in addition to using various air-cooling systems, the combustion liners and transition pieces are coated with a thermal barrier coating (TBC).

The TBC for the combustion system is a mix of an oxidation resistant MCrAlY-type bond coat (M: nickel or cobalt, Cr: chromium, Al: aluminium, and Y: yttrium), with a thickness varying from 150µm to 250µm, and a thermal barrier ceramic, usually ZrO_2-Y_2O_3 type, with a thickness of 300-600µm but occasionally could be as thick as 1-2mm for some combustors. The combustion coating is normally applied by air plasma spraying (APS) systems. Advanced low conductivity thermal barrier ceramic top coat with a mix of ZrO_2-$(Y,Nd,Yb)_2O_3$ has also been tried on more advanced aero engines. This could be an option for the industrial gas turbine in the future.

Turbine blade

The turbine blade alloy is designed primarily for resistance to creep deformation, but low cycle fatigue (LCF) resistance, strength/ductility, oxidation and corrosion resistance are also considered. With the expectation of transitioning to more flexible operation, the thermomechanical fatigue (TMF) properties of the blade alloy should be considered in line with the other requirements.

Historically, blade alloys were selected based on their creep capability. Since 1950 the creep capability of superalloys used for blading applications improved by an average of 50°C per decade. The creep strength of vacuum melted alloys was significantly increased by adding a higher ratio of precipitation hardened alloying elements (such as aluminium and titanium) as well as solid solution strengthening elements (like molybdenum, tungsten, tantalum, rhenium and most recently the ruthenium). A significant improvement in blade alloy creep performance was achieved by transitioning to directionally solidified or single crystal structures. The creep resistance of single crystal superalloys has been significantly increased by the addition of Re (~3% to 2nd generation, and 6% to 4th generation alloys) and Ru (up to 3% to the 5th generation alloys). However, this was at the expense of chromium, reducing the chromium content of the alloy to as low as 2-3wt% (for 4th generation alloys). Chromium is vital for hot corrosion resistance and this reduction brought into question the use of these exotic alloys for industrial gas turbine applications.

Ni-based polycrystalline cast alloys such as IN738, Rene80, GTD111, and Mar-M247, are widely used for rotating blades. Mar-M247 (or its newer variant) has the highest creep strength within the polycrystalline superalloy family, with an acceptable oxidation resistance but marginal hot corrosion performance. Therefore, application of appropriate hot corrosion resistant coatings is vital for achieving the expected operational life, even if operating in only a slightly corrosive environment. The directionally solidified alloys (GTD111DS, CM247, Mar-M002), as well as single crystal alloys (PWA1483, PWA1484, CMSX4, ReneN4, ReneN5) are also utilised for industrial gas turbine applications. The more advanced alloys such as CMSX-4, ReneN5 and PWA1484 contain a lower amount of chromium and they have limited hot corrosion life.

For stationary blades a mix of Ni-based or Co-based cast superalloys such as IN939, N-155, IN738, R80, GTD222, GTD444, and FSX-414, M509 (ECY-768) are used.

Oxidation/corrosion resistant coatings are applied to the blades to improve their service life. However, the durability of the blade alloys in corrosive environments largely depends on the amount of contaminants (such as Na, K, Cl and S) entering the combustion system via the intake or combustion fuel. For DES, high performance air filtration and frequent compressor washing would limit the contamination entering the turbine. The exterior surface of the blade aerofoil and in some cases the shank and tip, but not the blade root section, are coated with oxidation and hot corrosion resistant coatings, with MCrAlX composition (X: is minor additions of elements like Y, Si, or Hf). TBC to a thickness of about 300-600 microns are also considered for the front rows to reduce the metal temperature. The metallic coatings for the blades are often applied with a high velocity oxy-fuel system or a low-pressure plasma system, and the ceramic coating is applied by APS. However, for the high pressure aeroderivative blades, an Electron Beam Physical Vapour Deposition (EB-PVD) ceramic top coat is applied onto a platinum modified aluminised (Pt-Al) bond coat. The EB-PVD coating produces a columnar structure which has better strain tolerance than the APS splat-type microstructure. However, it is more sensitive to calcium, magnesium, aluminium and silicon related damage for the environment with dust ingestion.

The blade cooling cavities are coated in most cases to improve their oxidation and hot corrosion resistance. Simple aluminised coating (by pack, gel or vapour methods) is the preferred coating method for the internal cooling cavities.

Discs and rotors

Most compressor and turbine rotors are made of individual discs which are stacked and bolted together. However, there are a few versions of turbine rotors where the discs are welded together by electron beam welding. The alloy strength, ductility, creep, and LCF resistance are the basic requirements for most disc alloys. The sensitivity of the disc alloys to grain boundary oxidation and cracking should be evaluated for a given design and application. Stress assisted grain boundary oxidation cracking has been a major issue, causing several discs failures in the last two decades.

Compressor discs are most often made of low alloy steel or 12% chromium grades. On occasion, for use at the back of the compressor for high discharge units (>500°C, of aeroderivative applications) they may be made from nickel-based alloys (Inconel-718).

Turbine discs are made of low alloy steel, 12% chromium grades, as well as Fe-based and Ni-based superalloys such as A286, IN706, IN718, Nimonic 901, Waspaloy and more advanced U720Li. The alloys are forged and machined to the final finish. Some manufacturers perform the spin test of discs to further improve their properties. The homogeneity of the alloy composition and microstructure produced during alloy manufacturing and forging (i.e. recrystallisation during thermo-mechanical processing) is key to producing a high quality disc for a specific application.

Powder metallurgy disc alloys, which are often used for manufacturing aviation discs, have potential for industrial gas turbine applications but at much higher manufacturing costs.

Materials for microturbines

The core section of a microturbine is not cooled, and the blades and discs are manufactured as one piece in most applications. Ni-based polycrystalline cast alloys such as IN713C and MAR-M-247 are commonly used for microturbine applications.

Additive manufacturing (AM) is highly promising for producing the combined disc and blading for microturbines because of their smaller size. High performance oxide dispersion alloys have strong potential for this application.

HiETA Technologies are currently developing the capability to use both CM247LC and Haynes 282 alloys in the AM of high temperature turbomachinery and recuperators. This process will also enable cooled turbine disc and blades for increased operating temperatures (potentially 1200°C or higher).

Future development

Metallic material, and primarily Ni-based superalloys, are the alloy of choice for most blading applications for industrial gas turbines. However, with some success in AM technology, a better selection of AM alloys is expected to be available in the coming years for industrial gas turbines applications.

In addition, there is a high potential for implementing AM technology for hybrid manufacturing, to produce turbine components for enhanced performance in-service. An example could include producing a turbine blade with investment casting but building up the blade tip by AM with an alloy with better oxidation/cracking resistance. Or using Am to produce components with through wall coolings.

Material selection, durability, and maintenability

Material selection for the hot section of the gas turbines intended for Distributed Energy System should be optimised in a way to improve the durability and service life of the parts, in various operating environments.

Material selection drives the decision for maintenance intervals and estimating the associated operational costs of the engine, which is a key input when selecting an energy system for a decentralised power system. This includes the balance between the operational life and maintenance cost, and frequent replacement intervals.

In many cases, a very advanced alloy or coating system may not be the best answer for developing an engine. Using advanced single crystal blades for industrial gas turbines can have some draw backs, for example some alloys have been downgraded by engine manufacturers to more affordable, durable directionally solidified versions.

To be able to compete in the future diverse market, it is important to consider the durability and maintainability, in line with the technology level used for the materials, to have a reliable engine for the given application.

For small gas turbines stators, Alloy 713C is used in ANSALDO engine. It is a precipitation-hardenable nickel base superalloy, 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. The state-of-the-art rotor materials are Ni-based superalloys, such as MAR-M-247 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 is currently developing the 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 1200°C or more).

Regarding ceramic materials, silicon nitride is the preferred choice 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 the addition of Lutetium 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. Department of Energy 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.

1.5. Combustion

Three different types of combustors are used in gas turbines: cannular and annular combustion chambers, and a combination of both. While there exist three types of combustion technologies for gas turbines, namely:

- **Diffusion flame** – the flame is formed between the gas and oxidizer in the boundary layer. Only possible when the substrates are mixed by molecular or turbulent diffusion.

- **Premixed flame** – fuel is homogeneously mixed with air, and generally burns at lower combustion temperatures (600K below diffusion flames) to make low thermal NO_x emissions that require high turbulence and other provisions to achieve flame stability.

- **Catalytic combustion** – fuel is combusted inside a porous ceramic medium, aiming to prevent the formation of NO_x.

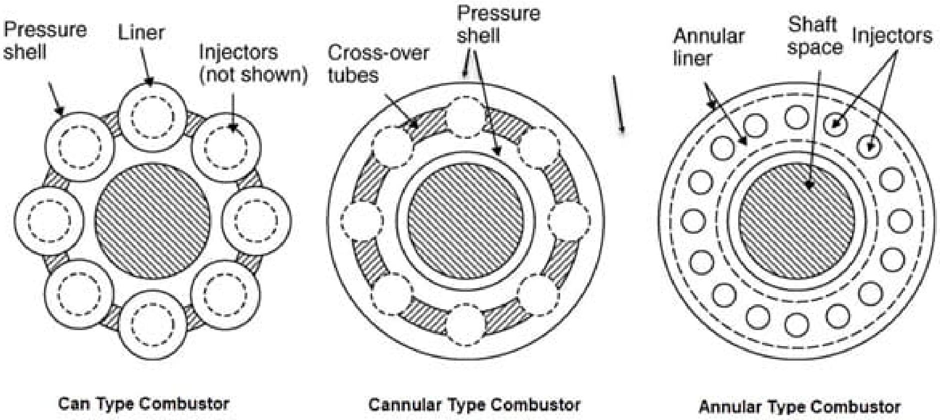

Figure 7: Classification of Combustion Chamber – Comparison Diagram [19]

Flame stabilization is fundamental for the efficient performance and reliable operation of the gas turbines. Usually, a flow reversal pattern is created to ensure that part of the hot exhaust gases is recirculated and mixed with the incoming air and fuel. The most common way of introducing flow recirculation is using swirlers. Swirl-stabilized combustors are characterized by strong shear regions and high turbulence, which allow good mixing. An alternative stabilization mechanism is 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 applications or very high combustor inlet temperatures. Wan and Fan [20] provide a detailed summary of recent progress in flame stabilization technology for micro-combustors.

Fuel Flexibility

Compared to piston engines, gas turbines can be operated with fuels with LHV without engine derating. The combustion systems of gas turbines can also be designed so that fuels can be easily burnt with lower octane number (increased auto-ignition/detonation tendency) as well as gases with heavier hydrocarbon components (C2+ like Propane, Ethan, Butane, etc.)[21] [22] [23]. Most gas turbines are currently operated with natural gas 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.

Biofuels

The use of biofuel in gas turbines 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 choking condition, the larger fuel flow rate would lead to a lower air demand from the compressor and, in general, an increase in 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, while both lead to a 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 a 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.

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

The effect of biofuels on the performance and emission characteristics has been widely studied in the literature, Altarazi et al. [24] provide a comprehensive review of challenges found and effects on gas turbine operation.

Indirect or External Firing

In externally fired micro gas turbines, the combustor is a separate component from the turbomachinery. The heat produced by external combustion is exchanged with air coming from the compressor in a high-temperature heat exchanger. 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 adding a gasifier into the system. The system would be similar to a Rankine cycle but with higher efficiency. Such systems are gaining momentum as they facilitate the coupling of renewable energy sources like biomass and solar energy with gas turbines [25]; novel configurations can be found in the literature [26].

Hydrogen

Hydrogen combustion in gas turbines does not only pose challenges to the technical requirements of the units, but also to the distribution and administration of the fuel itself. Hydrogen molecule is very small, having a greater tendency to leak than other gases. Moreover, the risk of embrittlement compromises many metals and materials commonly used in combustion and gas plumbing hardware [27], which can result in hydrogen leaks and premature failure of flow control and instrumentation equipment. Moreover, hydrogen leaks are a greater hazard than methane leaks due to the lower lean flammability limit (4% by volume at standard temperature and pressure). By mass, this translates into a lean flammability limit for hydrogen in air that is 90% lower than CH_4. This has a technical implication, translating into important purge considerations for failed starts. Hydrogen leaks are also problematic due to the lack of clear visualisation of the flame [28].

Even though the infrastructure for widespread combustion of hydrogen in gas turbines is not ready due to the above-mentioned challenges, it proposes the smallest technological barriers to store and maximise renewable utilisation with the retrofitting of existing infrastructure compared to other carbon-neutral fuel alternatives [29].

The current high hydrogen capabilities found in gas turbines exist with either diffusion or wet low NO_x type technologies, which are not comparable to dry low NO_x technology. The challenges in the implementation of low NO_x technologies revolve around flame dynamics, which shows vast differences compared to methane for which low NO_x technologies have been traditionally designed. These are:

- **Higher adiabatic flame temperature**. Increments of 5-10% with respect to methane have been observed [30]. The higher temperature results in higher NO_x formation, and potentially damages materials and coatings.

- **Higher flame velocity**, nearly an order of magnitude higher compared to methane [31]. This is one of the most problematic challenges as higher flame velocity can lead to flashback effect, when the flame velocity is higher than the airflow velocity, causing the flame to suddenly propagate upstream, leading to possible hardware damage. To avoid the flame flashing back, higher flow velocities that match the flame speed are needed. For example, a Dry low NO_x (DLN) nozzle under the same conditions would need roughly 10 times higher flow velocity for rich hydrogen fuel combustion.

- **LHV**. Hydrogen is eight times less dense than methane at the same pressure and temperature, but the lower LHV corresponds to half of the fuel flow needed for a traditional NG-fired gas turbines. Therefore, the volumetric LHV is roughly a third of NG, which means a hydrogen-fired gas turbines would need three times more fuel volume flow rate than a CH_4-fired plant. The volume flow rate is limited by the plumbing capacity, so the piping, valves and instrumentation for a hydrogen gas turbines would need to be accommodated to three times the size of one running on CH_4. This also affects the fuel gas pressure, which should be supplied at three times the traditional pressure to have the same volume-specific heating value as CH_4 at the same temperature. The increased pressure and volume flow rates further incur challenges in the cost and safety of the gas turbines design.

- **Fuel blend flexibility**. The first two challenges become exacerbated when mixed combustion is considered, as the combustor must be designed to overcome low flame speeds that promote lean blowout, and high flame speeds that promote flashback. This leaves a thin operating regime that can be maximised by limiting the percentage of hydrogen in the blend, which in turn limits the carbon-saving benefits of the unit [32].

Finally, it is worth mentioning that the challenges described above regarding flame speed, lean flammability, and observability of flame, are nonlinear with mixture fraction [33], and become much more significant as the hydrogen fraction in the blend is increased. In fact, the behaviour of the turbulent burning properties of hydrogen-methane is still an area of active research.

Hydrogen combustion and blending are covered in greater detail in the ETN Global reports Hydrogen Gas Turbines and Addressing the Challenges of Hydrogen Addition to natural gas.

Industry efforts to overcome combustion challenges

Some of the most relevant industrial efforts to overcome combustion challenges are listed below:

- **Axial Fuel Staging (AFS)** has the potential to increase turndown and lower emissions [34]. AFS can be applied in hydrogen combustion as in traditional natural gas, allowing for leaner main combustor operation, therefore lessening high NO_x production and flashback concerns for the main combustion zone.

- **Siemens** discussed in a report [35] the key physics and engineering challenges behind hydrogen combustion and propose a new advanced Ultra Low NO_x (ULN) head-end combustor with modified fuel injectors to combat flashback, and a fuel staging micromixing introduced as "distributed combustion system". Testing is presented on micromixing nozzles and full scale with greater than 80% hydrogen.

- **Mitsubishi Heavy Industries (MHI)** is exploring a multi-cluster diffusion burner consisting of many small diffusion burners for large-scale gas turbines. The objective is to develop many small, premixed flames that are robust against flashback, but with rapid air mixing to reduce temperatures and control NO_x emissions. The multi-cluster diffusion burner is designed to establish a lifted flame at the stagnation point of the recirculation zone. The lifted flame is key to the low NO_x strategy so that the separated fuel and air streams from the cluster can complete mixing upstream of the flame [36]. Another concept proposed by MHI for hydrogen-rich syngas fuels in oxygen-blown Integrated Coal Gasification Combined Cycle Power plants is a premixed combustor that transitions to a diffusion combustor for flashback prevention and injection of dilutants (water, steam, and/or nitrogen) for NO_x abatement.

- **Ansaldo** reported that a high hydrogen fuel supply will require attention to the fuel skid and controls to avoid leakage and maintain safe operation. It is discussed that rapid mixing is required for high hydrogen fuels, and more robust flame stabilization mechanisms are needed to handle changes in flame speed. Their flashback mitigation strategy considers higher premix exit velocities with appropriate boundary layer control [37].

It is found that most DLN/DLE/ULN systems are currently capable of handling 60% or less hydrogen content by volume in the fuel, and many OEMs have tested higher hydrogen fractions of 80% or 90%. More research is needed in the consideration of other combined cycles, including considerations of temperatures, purge requirements and exhaust water content, among others [38].

Ammonia

Liquid ammonia (NH_3) offers easier storage and transport due to a larger molecule. It does also count on existing infrastructure used in the agricultural sector that has been widely studied for reliability and safety. However, it poses even greater challenges in combustion than hydrogen. The flame temperature and speed are lower for liquid ammonia than for methane, but its higher nitrogen content leads to increased NO_x potential, even in premixed conditions [39]. For this reason, the DLE combustor does not perform well when fed with ammonia, the only advantage of this combustor is reducing emissions of unburned ammonia. The rich-burn, quick-quench and lean-burn (RQL) and the moderate or intense low-oxygen dilution (MILD) combustors show promising performance. The RQL combustor assures a stable flame in fuel-rich conditions. It is based on a two-stage combustor where in the first stage hydrogen is produced and then combusted in a second stage combustor working at MILD conditions, to reduce NO_x emissions. The MILD combustor is disadvantageous since it requires relatively high rates of dilution to maintain MILD conditions, which is challenging in terms of design and operation [40]. Valera-Medina et al. [41] explore the associated challenges of ammonia combustion in gas turbines in greater detail.

Recuperator

A gas turbine recuperator is a gas-to-gas heat exchanger for recovering gas turbine exhaust heat for pre-heating combustor entry air to save fuel. It is one of the critical components in gas turbine systems and is responsible for a significant fraction of the overall efficiency.

Recuperators are classified by their method of construction into three basic types: shell-and-tube, plate-fin, and primary surface recuperator [42] [43] [44]. All these high-temperature heat transfer systems have a common requirement for high materials performance.

In terms of (usually counterflow) heat exchanger design, the combination of requirements imposed by the gas turbine cycle makes the successful development of a recuperator an extraordinarily tough challenge. These requirements include high effectiveness, low-pressure losses, resistance to high temperatures, resistance to thermal shock and large temperature gradients in the structure, large pressure difference between hot and cold flow, compact design, minimal heat loss (insulation), and cost.

The most challenging objective for who design a recuperator is to guarantee a lifetime in terms of operating hours and thermal cycles that is compatible with the one of the other elements of the machinery.

The recuperator parameters that mainly affect the overall efficiency of the gas turbines are the effectiveness and the pressure losses. If the effectiveness increases (maintaining that same heat transfer coefficient), the exchange surface is higher, hence, 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 the geometry of the exchange surfaces must be optimized to find the best compromise (in terms of the overall efficiency of the machine) between heat transfer, compactness, and pressure losses. For these reasons, when defining the specifications, reference is usually made to the "equivalent effectiveness" using a formula that includes the thermal effectiveness, the air side pressure drops, and the exhaust gas side pressure drop.

Materials for recuperators

Since the effectiveness of a recuperator (thus the cycle efficiency) 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 the manufacturing process of the air cells. Therefore, fine-grained alloy foils with high creep strength at the maximum operating temperature are required.

The other property that the recuperator materials must provide is excellent oxidation resistance. As a result, alloy systems that could be considered for this duty include austenitic stainless steels, ferritic steels (e.g., FeCrAl alloys and their ODS variants) and nickel-based alloys (with high chromium and/or aluminium contents). An example alloy used for recuperator applications by a turbomachinery manufacturer, is MA 253, which is austenitic chromium-nickel steel alloyed with nitrogen and rare earth metals.

In addition to the material, the quality and type of welds are crucial in the manufacturing process of a recuperator. The expected lifetime of the recuperator is heavily dependent on the resistance to the fatigue cycles to which its welds are subjected.

Regarding composite materials for heat exchanger recuperators for high-efficiency gas turbines, the available literature suggests the best option is the application of silicon carbide.

Technological advances in manufacturing methods, such as AM, opened the door to building heat exchangers with a relatively new class of mathematically defined lattice structures known as Triply Periodic Minimal Surface.

This exhibits the minimum possible surface area and zero mean curvature within a specific volume. The property of a high surface-to-volume ratio improves compactness while still providing a tortuous path for fluid. The tortuosity abrupts the flow and leads to an enhanced heat transfer rate compared to the legacy heat exchangers and a reasonable pressure drop [45] [46]. The design freedom of AM provides the possibility of integrating a compact recuperator and combustor into one single component to remove the assembly time and complications and reduce the production cost. ETN Global Additive Manufacturing Working Group explores these topics in greater detail to provide R&D roadmaps.

1.6. Gas Turbines Operation: Reliability, Availability, and Maintainability

Gas turbine technology is considered essential during the energy transition because of its superior flexibility over other non-renewable counterparts. The dispatchable nature of gas turbines allows for a supporting role as RES are prioritised in DES, this entails that gas turbines will spend most of their lifetime in part-load, transient, and standby modes.

Feldmuller summarized the new operational trends as an increase in starts, fewer operating hours, more part load hours and load transients, a change for hot starts to cold starts, and a shift to unpredictable and new load regimes [47]. The increased cycling due to operational flexibility has adverse effects on gas turbines components, such as shorter equipment life, higher maintenance requirements, cost increases, and lower unit efficiency due to the continuous start-stops and ramping [48]; where the latter ultimately affects emissions per energy unit. The work by Farhat and Salvini explores in further detail the challenges associated with the increased flexibility requirements [49]. The need for flexible operation arising from the variability of RESs stresses the need for reliability, which is of greater concern with decreasing gas turbines size.

A reliable operation can be achieved using an engine monitoring and diagnostics system: real-time engine condition monitoring and fault diagnostics result in reduced operating and maintenance costs and increased component and engine life. Banihabib & Obrist presented a review on cycle modelling of micro gas turbines [50], whereas a full process of accurate micro gas turbines model adaptation to experimental data is presented by Manihabib & Assadi [51].

Aslanidou I. et al. review the state of the art of model-driven methods, data-driven methods, and hybrid methods for fault prognostics. It is found that most research in the area is focused on (i) condition assessment with only a few available measurements, (ii) performance prediction and diagnostics in off-design steady and transient conditions, (iii) real-time monitoring, (iv) multiple component fault diagnostics, and (v) reduction of the negative effects of noise and sensor bias on condition monitoring. A summary of the areas for gas turbines monitoring improvement is also provided, comprehending (i) fault isolation mechanisms, (ii) the need for tools to better extract, process and interpret data, (iii) hybrid diagnostic and prognostic approaches, and (iv) a consideration of user-friendliness in monitoring mechanisms to support the adoption of such [52].

The monitoring, control, and diagnostics of individual engines is commonplace today. However, the literature highlights that to allow the step change in the connection of small engines to the grid, a fleet monitoring system for micro gas turbines is required [53]. The extension or multiplication of existing solutions will not take advantage of all the possibilities available with the presence of a multitude of engines of the same family. It will also not be able to deal with the limited number of sensors used in smaller systems, which is essential to limit cost and make them competitive in the market. This requires a purpose-designed system that will compare data from different engines to assist the process [54].

Moreover, one of the predicted roles for small and medium gas turbines in the energy transition is the balancing between the energy demand and supply, mitigating RES variability in the grid. For the purpose of energy balancing, the part-load operation becomes a key factor affecting the integral efficiency of the system. Therefore, it is essential to improve the efficiency of the compressor and turbine in off-design conditions along with the design point.

A possibility outside of technical modifications for smaller-size gas turbines is the use of variable speed control to improve part-load operation. However, this requires a system capable of relating the imposed operational load to its optimal speed [55].

Another approach to improve the part-load performance in gas turbines is an increase in modularity, where one unit can be operating at optimal design load and other units be shut off as opposed to having one unit operating at less efficient off-design conditions. This enables higher component and integral efficiencies that result in lower operational costs. However, due to the increased initial capital expenditure and possible increment in maintenance costs, the configuration of the prime mover module should be carefully studied for each case, as it is likely to be beneficial only for applications where the gas turbines is expected to mostly operate off-design.

Finally, the configuration of DES is becoming increasingly complex as we shift towards hybrid multi-generation systems, where different products are generated from one or multiple sources. The literature highlights challenges with matching sizing with demand for multi-conversion technologies like gas turbines in multi-generation processes like CHP and combined, cooling, heat, and power (CCHP). There is a predominance to size and control the operation based on electrical demand, where thermal generation is a bonus from the electrical generation. Research advancements are needed for sizing the unit with consideration of both energetic demands and following a strategy that prioritizes both products to increase the integral efficiency of the system. Vivas et al. performed a review of energy management strategies for hybrid systems, where they highlight that the most adopted strategies only focus on satisfying the energetic demand, and despite their simplicity, show inefficient behaviour. Strategies that include technical and economic criteria are presented as more efficient and secure, with the adversity of being more complex and difficult to implement in real control applications. The authors highlight the need for further advancements in algorithms that allow multi-objective control in real systems [56].

1.7. Regulatory Framework of DES

Energy generation is gradually transitioning from the largely predominant centralized generation due to rising concern over climate change, dropping technology costs, and social innovation opportunities. All the developed and developing nations are adopting and promoting RES and distributed generation in their capacities to reduce their reliance on fossil fuels and are increasing the penetration of RES for future energy security and climate change. All have formulated numerous guidelines, policies, regulations, and standards, and set goals for the maximum utilization and deployment of RES and DES. However, decentralization has several advantages, but it also raises concerns about governance. The growing amount of decentralized generation in the energy mix brings more benefits than challenges, but it surely complicates the tasks of authorities responsible for ensuring an adequate, clean, and affordable energy supply. Due to the challenges and ambiguities in the system, adequate policies and their amendments are required to counteract the existing problems and increase the development, utilisation, and deployment of DES.

Existing regulatory framework

To avoid dangerous climate change, a long-term goal to limit global warming well below 2°C, preferably to 1.5°C, compared to pre-industrial levels is set under the first-ever universal, legally binding global climate change agreement called the Paris agreement [57] [58] [59]. The EU's targets are in line with the global climate actions, which are to be climate-neutral by 2050 – an economy with net-zero greenhouse gas emissions with intermediate reductions to 55% of their 1990 levels by 2030 [60]. To achieve these climate change and energy targets in an affordable way, there is a requirement for the secure and effective implementation of RES, enhanced energy efficient technologies, and carbon capture and storage (CCS) [61].

Advancements in DES technologies like gas turbines and micro gas turbines are also essential to meet Europe's 2030 and 2050 targets. Though there are no specific regulations formulated for decentralised generation in the EU, there are different directives ((EU) 2018/2001, 2018/2002, 2019/944, and 2013/347/EC, etc. [62] [63] [64] [65] and framework programmes for research and innovation (as of January 2021, the 8th framework programme, "Horizon 2020", will be replaced by the 9th framework programme, "Horizon Europe" [66] [67] launched by the European Commission for energy efficiency, RES, and energy infrastructure . There was a direct directive (2004/8/EC) on the promotion of cogeneration, but now it is no longer in force and has been replaced by the directive 2012/27/EU on energy efficiency [68] [69].These EU directives should be achieved by each member state by adopting their own laws on how to achieve the goals. The amended directives based on EU's penetration goals for RES (at least 32% by 2030) and energy efficiency target (at least 39% by 2030) will encourage increased DG deployment among its member states, as policy effects are not exclusive and linear.

The implementation of early support schemes in Germany and Denmark has resulted in greater market penetration and growth for DES and a more sophisticated network. Germany has established the fastest growing renewable and decentralized energy economy in Europe. This is an outcome of the various incentives and subsidies based on the "Renewable Energy Law (German: Erneuerbare-Energien-Gesetz)" and its amendments, along with the set grid-connection standards for the medium and low voltage distributed network for DES. The share of decentralized generation in Denmark accounts for more than 50% of the total electricity produced, the majority of which is wind. As of 2021, 48.6% of the total electricity produced was from decentralized CHP. The reasons, apart from being the first mover, are the priority given to grid access and the long-term targets. The Danish government has also established the Act on Natural Gas Supply, the Heat Supply Act, and the Electricity Supply Act to provide support to the DES [70] [71].

In the UK, the DES contributes around 10% of the total electricity production, which is sufficiently low as compared to other European countries. Though the government has implemented a number of policy schemes over time to encourage the expansion of decentralized and renewable energy systems: a renewable energy target, Feed in Tariff, Renewable Obligation, contracts for differences, and a capacity market. There are still a lot of barriers that explain the situation, including grid access, licensing, uncertainty in policy support, and soft measures like social acceptance and consumer inconvenience [72] [73] [74].

The United States energy policy established a framework to promote the deployment of RES and DES in the US power sector, which was established by the Energy Policy Act of 2005. The success of decentralised PV in the US has developed the interests of many nations in the distinctive business model as well as policy and regulatory approaches (federal tax benefits, state incentives, net metering, etc.). The New York Public Service Commission) envisions the Digital signal processor as a digital marketplace that enables two-way information and energy transactions between all grid participants (DG owners and utility providers). There is also a huge increment in the total amount of electricity produced from RES due to both state and federal support. The drivers for this growth are the federal tax incentive, renewable portfolio standards, specific incentives for technologies, and the advancement of technology and its cost reduction [75] [76] [77] [78].

The Public Utilities Regulatory Policies Act (PURPA), along with the broader initiatives to deregulate the energy business, had a significant impact on co-generation installations in the United States. This law permits the sale of electricity at a utility-avoided cost. There is a 10% investment tax credit for all the CHP projects up to 50 MW that exceed 60% energy efficiency under the Bipartisan Budget Act of 2018. The act also provided additional benefits for CHP projects, such as depreciation allowances. Co-generation in the US is also supported by the low and stable price of natural gas. Although PURPA has contributed to a noticeable increase in gas-fired CHPs in commercial, residential, and public buildings, there has not been much growth in new installations in the past few years [79].

The Chinese government has also introduced a number of policy schemes in support of RES and DES which has created striking opportunities for DES such as natural gas decentralized generation, decentralized wind power generation, and more specifically, PV decentralized generation. These supports majorly include in terms of targets, subsidies, incentives, and grid connection. Japan has also gradually established a decentralized energy system with an emphasis on cogeneration and PV generation. Some of the relevant support for the DG projects includes investment and financing mechanisms, tax preferences, grid-connected policies, and regulations [80] [81] [82].

Additionally, various laws and procedures were created and put into practice in numerous nations, including Russia, Brazil, Iran, India, Mexico, and South Africa, etc., to encourage the development and deployment of decentralized energy systems [83] [84] [85].

With policy support in various countries providing incentives to CHP and RES, gas turbines and micro gas turbines seems a potential future in the coming years. Though, Not having any specific support for the technologies based on the advantages of primary energy savings and lower emissions compares to other technologies sometimes outweighs the policy support. Since these technologies face both market and legislative barriers, changes and evolution of the regulatory framework are clearly necessary to make them more attractive, financially, and to facilitate the ease with which they can be utilised and deployed.

1.8. Policy Recommendations

The decarbonisation of the future European energy system needs to ensure at least the same, if not greater, level of reliability. It is obvious that the rising energy demand cannot be met without a variety of sources, which will also increase supply security. As a result of this mix of sources, the power system is facing an increased level of uncertainty and there are divergent opinions regarding the structure and governance of such system. Additionally, the expansion of DES and RES would require more advanced and adaptable transmission infrastructure, which is not compatible with the current state of the traditional infrastructure. For many years to come, the governance decisions made by responsible authorities will shape energy systems. Although it is widely acknowledged that the future of energy will be at least somewhat decentralized, there are clashing opinions on the structure and administration of such a system.

While focusing on the development of future RES technologies and their implementation in the networks, there is a risk to leave aside the issues of system and market integration, which will become a critical priority in the coming years. As understood from the previous section, in many nations, hybrid renewable and alternative energy source systems have been successful due to favouring policies, schemes and acts. However, to achieve the mandatory environmental and energy targets there is a need for additional support from the government.

It is necessary to make a balance of the entire energy system and adopt 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 decarbonization of the energy system. To make sure that an increasing contribution from decentralized energy is now included in most of the local and national government policy worldwide. Also, the Incentive schemes applied to the RES has lead to the corresponding growth to DES. However, there are still several policy and regulatory obstacles limiting the development of DG technologies. Besides the security of supply, the connection to the distribution grids and networks is the main issue. The technical requirements for grid connection are unclear, and respondents report that response times and collaboration with some grid operators are inadequate. How to incorporate potential public benefits in the tariffs has been largely discussed in Europe. The countries with the most successful decentralized generation are the one with the large number of DSOs. It is acknowledged from the US electric market that decentralized generation is most likely adopted by the private utilities than the public ones. The same support measure has differing effects on consumer- and utility-owned DG [86] [87].

Along with these, support for the supplemental DG technologies, such as storage and smart grids, will enhance the overall DES business case. To achieve trouble-free Plug and Play of DES, the support and enhancement of microgrid cannot be ignored and should be developed simultaneously. The policies supporting microgrid and DES are unavoidably related, and the integration of these policies should always be considered. All these options should be developed in parallel with the RES technologies, leaving some uncertainties in the market [88].

The next step to enhancing the installation of DG technologies should also be to allow users to generate their own power and transmit the excess to their neighbours, which has been addressed and is in the process of implementation in some nations. Due to the same transaction costs for owners of small power generation technologies and large power plants, there is also a need for additional support for small-scale DGs like micro gas turbines, which limits the competitiveness of small DG technologies. It has been observed that the transition towards more market-based support is required for fostering DG deployment than the usual historical support.

Additionally, government policy implementation delays are a significant hurdle for such a system. Finally, the role of regulatory measures is viewed as more nuanced. It is important to recognize that not all technologies are created equal in terms of scale or performance. It is unrealistic to expect them all to perform consistently under the same market and regulatory conditions though there is an ongoing debate about the technological specific support specially in Germany and Denmark. Along with more effective and streamlined policy and regulatory framework, there is an additional requirement for infrastructural and institutional support in terms of financing, marketing, capacity building, and strong coordination among key stakeholders, which is often neglected [89].

2. Integrating gas turbines technologies to DES: a new challenge

2.1. Identification of technologies to resolve the trilemma

CHP is a general term to define/represent an application where electricity and thermal power are produced concurrently for direct use and typically with higher efficiency levels than if produced separately. The main objective of such application is to produce on-site power and utilize, as directly as possible, all heat that is released/produced (by the on-site power generation) in a "connected" industrial process, to produce steam, hot water, or even chilled water (through tri-generation). To achieve the above, a very different range of technologies and fuels could be utilized depending upon the industrial application supported by the CHP plant.

There are significant variations on the CHP plant design, however at macro-level we could differentiate between:

- individual facility/building when the CHP plant is directly serving a single (or limited) amount of end-user's processes like in case of a Gas Turbine generator feeding a papermill or a ceramic plant/production line; or
- district/utility services when the CHP is serving a multiple quantity of end-users like in case of Gas Turbine generator feeding electricity to the grid and heating power to a district/city's neighbour.

Few of the key advantages of a CHP plant can be identified in the following list:

- High energy efficiency thanks to a direct utilization of the electricity and thermal energy produced; and
- 24/7 continues power production with minimum downtime associated with "programmable" maintenance interventions.
- Variable load range of electrical and thermal production that can enable a variety of production requirements like in batch production (i.e. in pharma plants).
- Resilient power production that can compensate grid outages and/or substitute grid connection requirements.
- Enabler to the penetration and full integration of other distributed energy technologies (i.e. Solar PV, Energy Storage) by providing grid support services for example with stabilization of frequency, voltage and power stability or synchronous generators.

The most distinguishing characteristic is the high efficiency level thanks to the reduction of heat's waste and distribution losses (since it's a concurrent/local use of the energy produced) that enables to reach up to 80% of efficiency levels compared to much lower (~30-45%) levels for other technologies (i.e. gas fired boiler for steam production). Such a higher efficiency level directly translates in lower carbon emissions for the same energy produced, therefore lower CO_2 for CHP then separate production of heat and electricity.

In addition to standard application of (micro-) gas turbines for power and heat generation could be some un-conventional applications considered. There were some examples in the past with following "characteristic":

- Required modification of the gas turbines to allow an integration with a different process.
- The heat source was in most cases not only based on internal combustion but resulting from another component (e.g. fuel cell, solar) or process.
- The modified and integrated gas turbines was operating outside the design operating range (temperature, pressure ratio, etc).
- The major benefit was not resulting from the energy output of the gas turbines but from an overall improved performance of the integrated system (e.g. improved energy efficiency, reduced emission, higher production rate of a given process, etc.).

The basic and later on modified gas turbines was also well suited when allowing for variable speed operation and 4-quadrant capability of the motor/generator unit. As this allowed for a well-controlled start up, shut down and load change of the gas turbines in connection with the component/process.

2.2. Today's application of small gas turbines and micro gas turbines

The primary application of micro- and industrial gas turbines today is in individual applications, which produce heat and electricity for one end user. The significant advantage of these applications is the efficiency gain compared to separate production. The technology is well established in these applications ranging from small to medium industrial plants and larger buildings with high heat demand, like Hospitals, Hotels, and swimming pools. In most applications, these gas turbines are still operated with fossil fuels like natural gas. However, due to its fuel flexibility (see chapter 1), the systems would be well suited to work with renewable fuels like biogas, hydrogen, and syngas.

Moreover, due to the lower system complexity, most gas turbines could be adapted to renewable fuels without exchanging the whole gas turbine. Besides the fuel flexibility, the systems only need a limited number of renewable fuels due to their size. If these can be produced nearby, it would reduce the logistic efforts to a minimum. Therefore, even in today's applications, there is a great potential to shift from fossil to renewable fuels and reduce CO_2 emissions significantly. In the following, some examples for today's application are given, which show the advantages of the technology and already demonstrate the fuel flexibility and suitability for renewable fuels.

Example I –Combined Cooling Heat and Power in hotel industry

Due to the high and concomitant thermal and electrical demand, the hotel sector can achieve interesting energy savings by using cogeneration or trigeneration. Among the various applications, the one described below combines two microturbine CHP with an absorption chiller and a biomass boiler. Microturbines, known for their great compactness and high electrical and thermal efficiency, have the advantage of having low polluting emissions. As expected by hospitality sector, they emit few vibrations and operate quietly, also reducing noise pollution. More than 30% of the total energy consumption of the resort is autonomously produced thanks to cogeneration. The Biomass System is fed by wood chips and generates thermal energy. This type of plant allows the resorts to considerably reduces carbon dioxide emissions and enables the use of local logging waste to be optimized, thereby reducing the environmental impact to a minimum. In this specific case the Biomass system covers about 38% of the thermal energy demand. Absorption chiller generates cooling by using the exchange heat of the microturbines and biomass boiler. This enables the potential of the plants installed to be fully exploited over a wide range of hours.

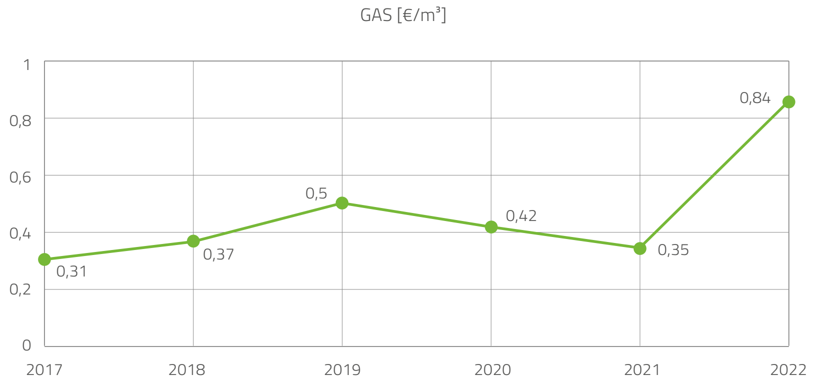

Figure 8: Actual cost for natural gas

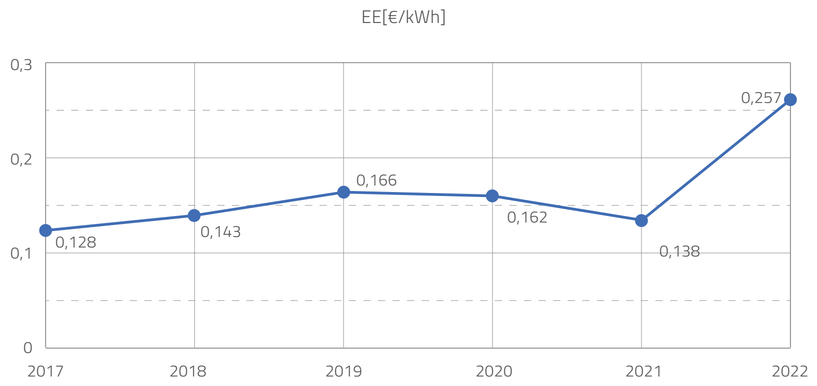

Figure 9: Actual cost for electricity

According with the above actual cost for natural gas and electricity it is possible to estimate a rough annual saving obtained by the Hotel operating a 100kW microturbine CHP for 6500 hours over the last few years. The savings were also compared with alternative means of thermal energy production.

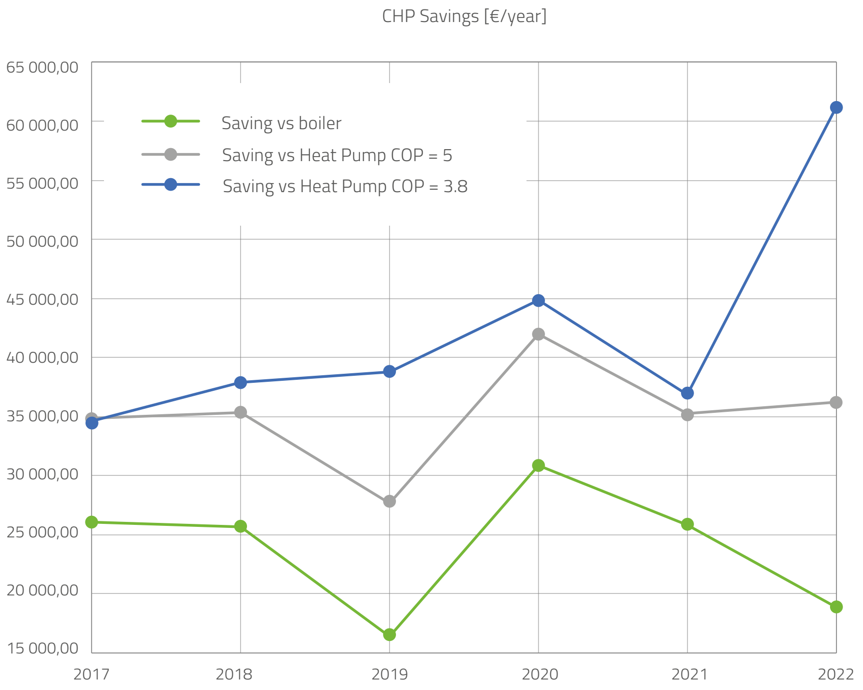

Figure 10: Estimate of annual saving obtained by the hotel operating one 100kW microturbine CHP for 6500 hours

Example II – Generic CHP plant

A simplified CHP plant based on gas turbine can be found in multiple industrial sectors where both electricity and thermal power are utilised concurrently for the plant's process needs. These typical applications can include, among others:

- Food and beverages processing where significant quantities of heat are required (i.e., brewery, dairy, oil & seeds, etc.)
- Chemical plants
- Paper and tissue processing
- Ceramic tiles production
- District heating where in such case the utilization of thermal power is not co-located since the heat is typically distributed to a district of houses/buildings
- Petrochemical plants

An example of such simplified plant design is represented in the following graph where the exhaust gases from the turbine's exhaust are feeding a waste heat recovery unit to enable the production of steam and hot water that will be feeding customer main process. At the same time the electricity produced by the gas turbine's generator will be feeding the overall plant needs and beyond by connecting to the grid as needed.

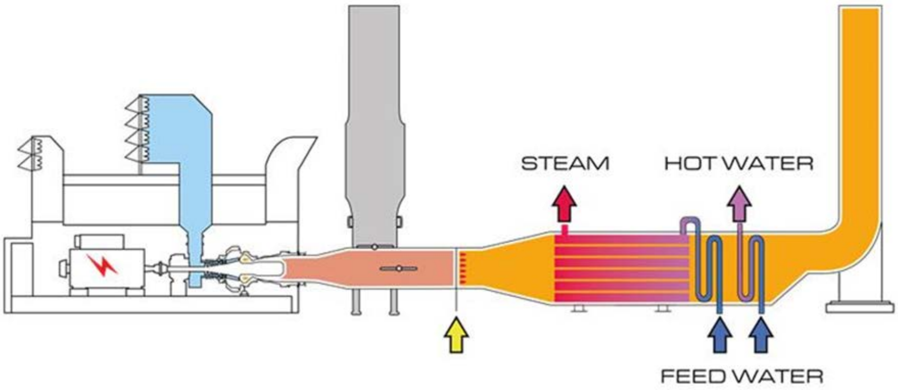

Figure 11: Sketch of a simplified CHP
© Solar Turbines

As an example, for such type of application we can assume a CHP plan serving an airport electricity and heat/chilling needs; for such an application the main drivers are:

- Stable and reliable electricity to support a critical operation like an airport.
- Saving on the overall energy bills through increased efficiency obtained via CHP.

A simulation of the plant economics assuming a 21.5 MWe load shows about 23% of savings compared to a yearly average electricity from the grid.

Example III – CHP plant for a Tissue Machine

As an example, here below is represented a plant lay-out scheme where the Gas Turbine (in blue) is utilizing fuel (i.e., biogas, natural gas, hydrogen, and natural gas etc.) producing electrical power directly feeding the tissue plant and, concurrently, sending the hot exhaust gases to the Yankee Hood (tissue direct dryer) and boiler for producing steam used in the tissue processing machine.

The Yankee Hood is a highly sophisticated part of a tissue's product plant that uses very high temperature air for high-speed drying of the produced material. This piece of equipment is the ideal combination with a Gas Turbine that feeding with its exhaust gases the air intake of the Yankee Hood makes for a high efficiency direct use of the thermal output therefore resulting in a fuel economic drying system.

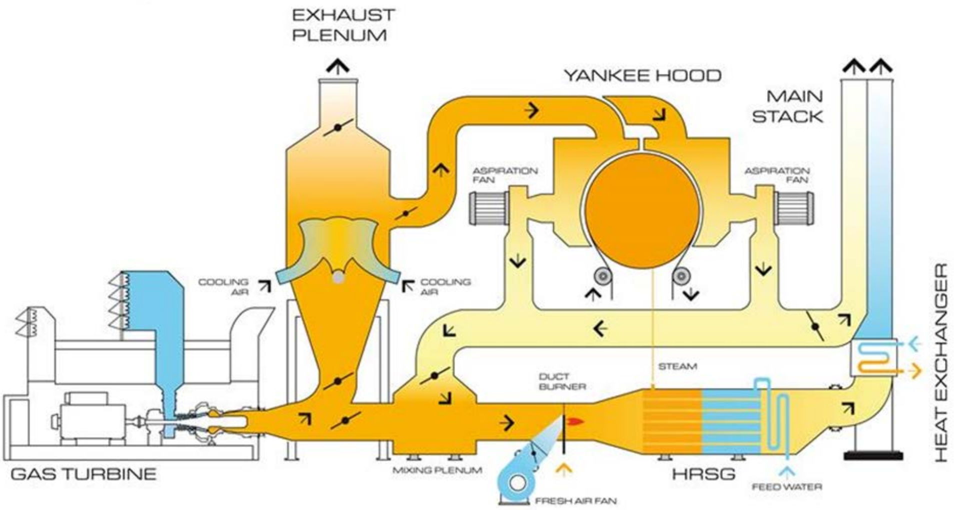

Figure 12: Example of CHP application in a tissue producing process
© Solar Turbines

The advantages associated with a cogeneration plant based on a gas turbine can be summarized as follow:

- Reduction in the plant operating costs
- Reduction in CO_2 process footprint
- Increased production quantity
- Better product quality

A simulation on the various impacts assuming a base Scenario of:

- 16.5 MW
- 30 t/h steam

The impact on the operating costs can be summarized by the following chart.

Additionally, through the utilization of a gas turbine operation, we can expect to avoid CO_2 emissions between 21% and 28% by leveraging a CHP installation associated with a digitally enabled optimization tool.

Note: This is calculated as suming a yearly average of EU energy mix for the electricity needs and heat via natural gas fired boiler.

Example IV – CHP plant for a Ceramic Industry

Another typical application for cogeneration industry with gas turbine is the utilization into a Ceramic Plant utilizing spray dryer technologies. Also, in such application there is a direct utilization of both:

- electricity produced by the generator moved by the gas turbine that is utilized for the plant energy needs as well as for feeding the grid, in some cases with access to demand/response scheme.
- thermal energy in the exhaust gases of the gas turbine is directly feeding the spray dryers in the ceramic process that drive the drying process for the powder used for the manufacturing of ceramic tiles.

The complexity of the plant lay-out is strongly dependent upon the size of the plant itself, as well as the type of final products from the production line, however a basic scheme of the proposed plant is illustrated in the following diagram.

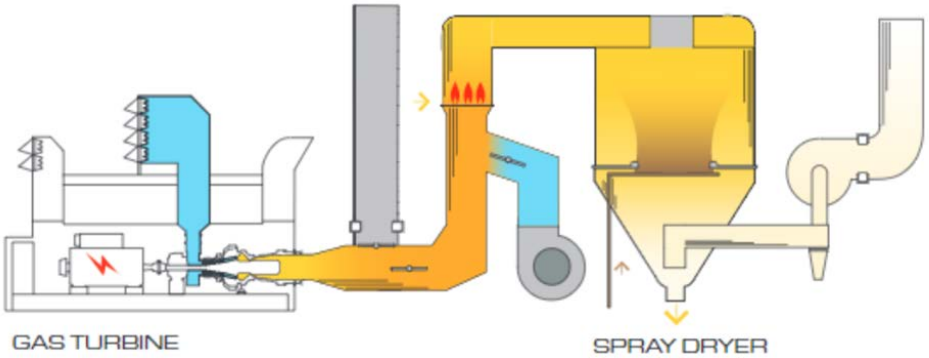

Figure 13Sketch of CHP for a ceramic plant utilizing spray dryer technologies
© Solar Turbines

There are several significant advantages associated with a cogeneration plant based on a gas turbine that can be summarized as follow:

- Lower primary energy consumption, resulting in reduced energy bills.
- Availability of reliable and stable electricity and heat.
- Reduction in CO_2 emissions versus conventional generation.

A simulation of the plant economics assuming an 8 MWe load shows about +44% if savings compared to a yearly average electricity from the grid and heat via natural gas fired boiler.

Example V- Biogas production / micro gas turbines integration

The concept has been designed for the conversation of waste to biogas onsite and its later use as fuel in a micro gas turbine. Bio2CHP is a company that has started with the design of gasifier and has coupled it with an ICE. Bio2CHP has a prototype installed in a winery yard that produces heat and power during the whole year with their own waste. The next step would be to replace the ICE with a micro gas turbine.

2.3. Gas Turbines Integration in DES: Integration of Fluctuating RES

Because of their high load flexibility, part load efficiency, and fast start-up and shutdown times, gas turbines are outstandingly suitable for integrating fluctuating RES in complex energy systems. Such an energy system can be a separate local grid of an industrial plant or the distribution grid of a residential quarter with many independent consumers and producers. The energy system can make use of different RES like wind, photo-voltaic, and geothermal heat depending on the availability. And these sources can be combined with heat and battery storage or hydrogen production with electrolysers. *Figure 14* shows an illustration of a selection of possible technologies. Such a system can, first of all, meet the consumer's demands and help maximize the use of self produces RES while providing the necessary security of supply. Moreover, through a connection to the power grid, the owner can sell electricity if prices are high and use electricity to fill its storage if prices of green electricity are low.

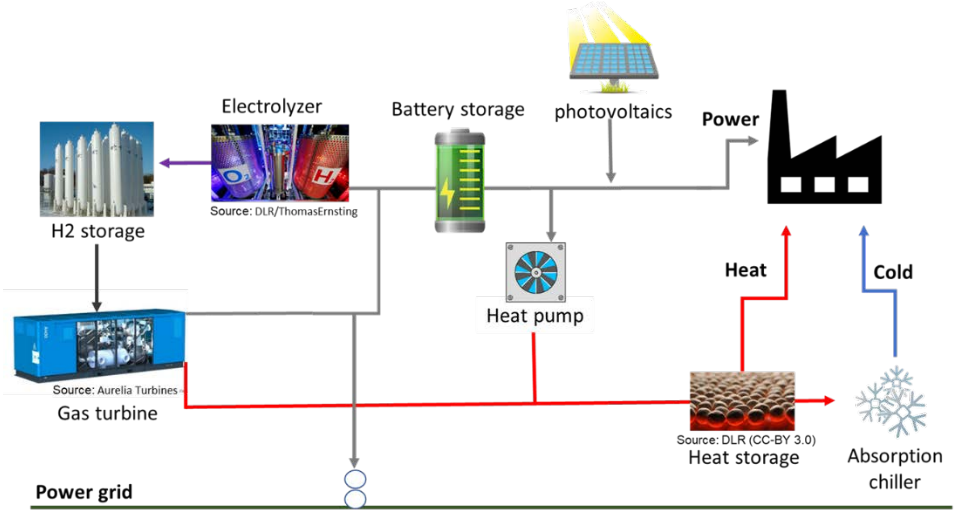

Figure 14: Integration of RES in DES

Until today, the combination of RES with a gas turbine as a balancing component for the fluctuating sources and in combination with hydrogen or biogas as long-term energy storage is an exception. Typically, the power grid serves as a backup. But with increasing renewable electricity and more volatile power and gas prices, such combinations become more and more interesting.

Of course, optimization of the gas turbine technology for such application scenarios is necessary to optimize the economic benefit. Moreover, adapting to specific fuels or combining different fuels is advantageous to increase independence, but today's gas turbine technology can already serve such applications.

The significant development aspects focus on the overall control systems, which enable an intelligent use and combination of different technologies—maximizing the use of RES while minimizing maintenance efforts.

Off-Grid and Grid Power-to-Power with Micro Gas Turbine and BESS

Integration of a Power-to-Power Energy Storage System (P2P-ESS) based on a hydrogen driven micro gas turbine is foreseen as a technology that will help with the integration of RES. The design of the systems changes depending on whether considering a grid-connected or off-grid application. For the latter, the P2P-ESS needs to seasonally store hydrogen so that the systems are not oversized. Whereas for grid-connected applications, there must be a balance between the self-production power ratio (power produced onsite/power imported from grid) and the cost of the system.

Antonio Escamilla et Al. [90] carried out a techno-economic study for an off-grid application that uses a P2P-ESS based on a hydrogen driven micro gas turbine to power an application that consumes 30 kWe *(Figure 15)* for three different cities in Europe – Palermo (IT), Frankfurt (DE), and Newcastle upon Tyne (UK). The figures-of-merit used were both the Levelized Cost of Energy (LCOE) LCOH. The LCOH is highly influenced by the seasonal storage, being 50% of the final LCOH, and highly increased when increasing the latitude of the location (North Hemisphere). Regarding the $LCOE_{mgt}$, most of the 95% of the cost is due to the cost of hydrogen, and therefore, the cost of the micro gas turbine system is not as relevant as the cost of for this application. The is 1.49 €/kWh, 2.19 €/kWh and 2.57 €/kWh for the cities of Palermo, Frankfurt, and Newcastle. However, the average value of the $\overline{LCOE}$ for the application, considering PV and micro gas turbine, is 0.86 €/kWh, 1.27 €/kWh, and 1.50 €/kWh, respectively.

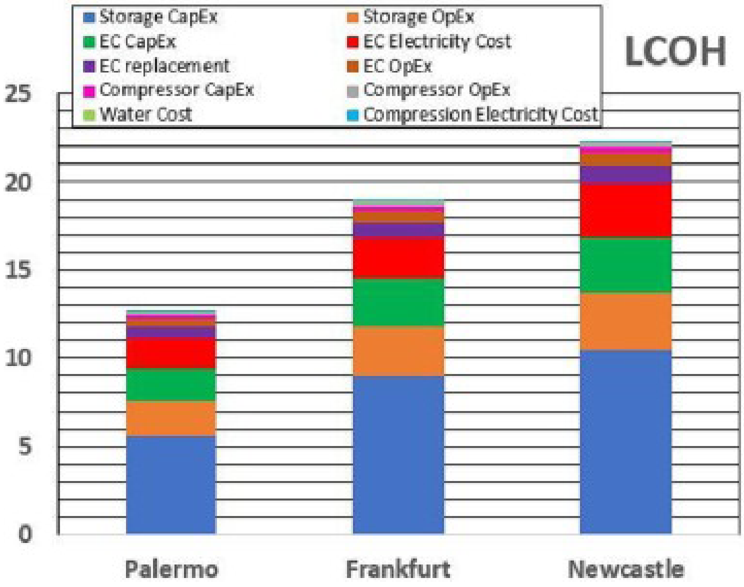

Figure 15: Comparison of LCOH of an off-grid application in Palermo, Frankfurt, and Newcastle

With the aim of reducing the footprint of the systems involved as well as $\overline{LCOE}$, Antonio Escamilla et Al. also carried out the same study but hybridizing the P2P-ESS with a Battery Energy Storage System (BESS). The introduction of a BESS reduced the amount of seasonal storage, but also the number of operating hours of the electrolyser and micro gas turbine. Thus, the LCOH and $LCOE_{mgt}$ increased. However, since the $LCOE_{BESS}$ is much lower than the $LCOE_{mgt}$, 0.25 €/kWh, the $\overline{LCOE}$ for the city of Palermo went down to 0.69 €/kWh. The footprint of the PV and electrolyser went down by 32.5% and 45%.

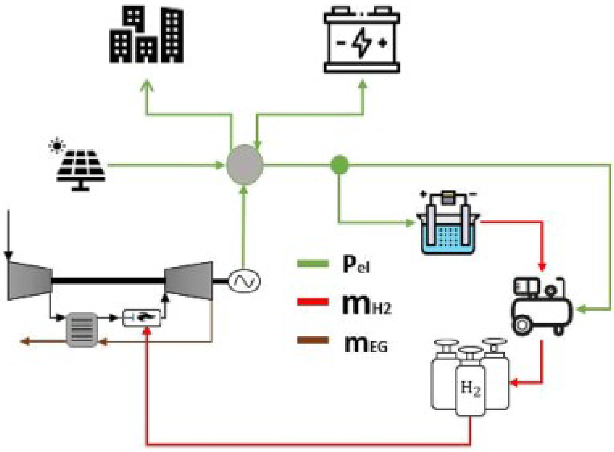

Figure 16: P2-ESS with BESS

Another example of Power-to-Hydrogen-to-Power application is a comparative study from Tilocca et al.[91] They developed a methodology to compare different technologies taking into account financial parameters (LCOE), reliability and emissions altogether. Their work studies an independent rural community in South Wales of 220 houses, accounting for the electrical and thermal demand. The energy system comprises 2MW of installed wind turbines and 2MW of solar panels. The surplus power is converted into hydrogen by an electrolyser and stored in high-pressure vessels. The authors considered an 800kW installation with two parallel units (2x400kW) to deliver backup power with the desired availability. Four prime mover technologies are assessed: reciprocating engines, fuel cells and two different gas turbine layouts. The gas turbine layouts are recuperated (GT-R) and intercooled recuperated (GT-ICR). The study makes an evaluation bringing in uncertainty quantification for the technical and financial input parameters.

Figure 17 shows the comparison of median LCOE. The study confirms the poor competitiveness of single-shaft micro-to-small GT-Rs because of their low electrical efficiency, which drives up the energy costs and, eventually, the LCOE.

The GT-ICR higher electrical efficiency, even at part-load operations, compensates for having a higher capital cost than ICEs. In addition, gas turbines feature superior availability and reduced NO_x emissions. All this combined makes GT-ICR the most competitive technology for this particular application, according to the overall assessment which combines the LCOE score with the availability and emission scores.

Reciprocating engines are the overall second-best technology thanks to a low capital cost and good electrical performance. Their median LCOE is comparable with GT-ICR. Finally, fuel cells are not expected to be competitive on the route to 2030, given their high projected capital and service costs.

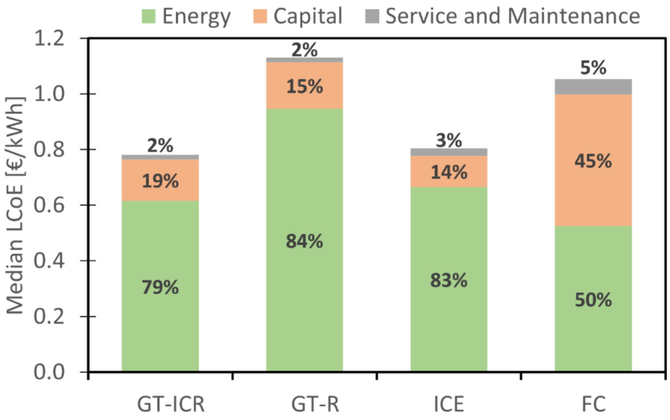

Figure 17: Median Levelised Cost of Electricity for the different prime mover technologies[92]

2.4. Gas Turbines Integration in DES: Future Applications

While integrating gas turbines into complex energy systems is one way to increase the use of fluctuating RES, another way is to use RES in the gas turbine directly. For such applications, the gas turbine typically has to be modified because the RES is integrated into the gas turbine cycle. Such an integration needs a significant adaptation of the gas turbine. The following paragraphs give two examples of possible ways to integrate RES. The first one it the direct integration and use of concentrated solar heat to heat the working medium of the gas turbine. The second one is the direct integration of heat storage, which can be used to store excess green electricity and produce electricity when needed.

Concentrated Solar Power (CSP)

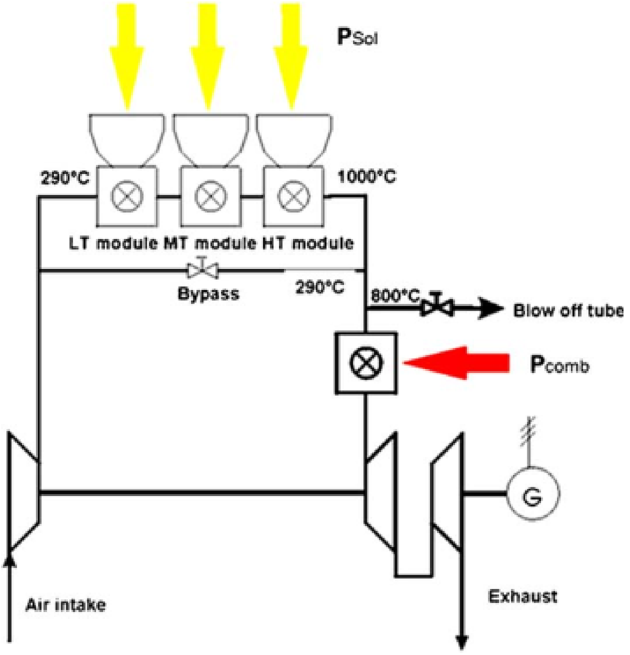

Figure 18: A central receiver system (CRS)

Micro gas turbines driven by CSP are currently considered a reliable technology for simultaneous heat and power generation. CSP plants use solar radiation to heat a heat transfer fluid (HTF) of a power cycle. The solar irradiance is reflected through some reflectors onto a receiver (or absorber) where it is concentrated and inside which the HTF heats up. Among the four existing technologies, the CRS and parabolic dish are the most suitable to drive micro gas turbines as they allow to operate at high temperature. In CRS-driven or solarized micro gas turbines, the input thermal power is supplied partially or totally from CSP, using the ability of CRS to operate at temperatures over 900 °C [93]. In the EU SOLGATE project (2002) was explored the technical feasibility of a solar-hybrid power system composed of a 230 kW_e modified micro gas turbines coupled with a new solar receiver concept [94] [95]. A solar-hybrid cogeneration system based on a 100 kW_e micro gas turbine was developed in the EU SOLHYCO project (2010) [96]. A CRS-driven combined cycle composed of a 60 kW_e bottoming organic Rankine cycle and molten salt thermal energy storage (TES) was commissioned in the EU POLYPHEM project (2018) [97].

Buck and Friedmann analysed the thermo-economic performance of a solar-hybrid micro gas turbine cogeneration system of 100 kW_e operating with natural gas, concluding that the application for touristic resorts can be a significant market potential in the future for this technology [98]. Giostri et al. analysed a small-scale CRS operating with micro gas turbines in the power range of 100–200 kW_e, displaying that this technology can achieve a yearly solar-to-electricity efficiency of 16.3% and a LCOE of 17.5 c€ kWh_e^{-1} [99]. Babaelahi and Jafari investigated on a micro gas turbine for a solar-hybrid application concluding that the thermal and exegetic efficiency were about 34% and 35%, respectively [100]. Landman et al. presented a techno-economic sensitivity analysis of heliostat field parameters for a micro gas turbine of 100 kW_e and CRS, pointing out that a solar multiple of 1.8 allows to obtain a low LCOE [101]. Aichmayer et al. analyzed three different micro gas turbine layouts to assess their suitability as small-scale hybrid solar CRS power plants and carried out a thermo-economic analysis. Among these, the recuperated engine allowed a LCOE between 25 and 30 c€ kWh_e^{-1} [102]. Nelson et al. developed and validated a steady state thermodynamic model of a 100 kW_e (165 kW_{th}) micro gas turbine coupled with a CRS to offset natural gas consumption. The results illustrated a 31.5% electrical efficiency and 83.2% cogeneration efficiency at nominal condition [103]. Ssebabi et al. proposed the performance prediction map of a 20 kW_e micro gas turbine under solar-hybrid operation to display possible operating ranges and control strategies [104]. This analysis led to a cycle thermal efficiency of 8% and to highlight the influence that the system components losses have on the micro gas turbines. Alshahrani et al. conducted a performance assessment for a 100 kW_e solar-biogas micro gas turbine integrated in a CRS, considering the effect of meteorological condition, recuperator effectiveness, solar share, and components performance [105].

Research on the CRS-driven micro gas turbines has focused on open-cycle hybrid systems, where a backup combustor supplements the solar receiver to achieve the nominal HTF temperature [106]. The development of new unconventional applications of micro gas turbines includes new closed cycle layouts externally fired or unfired. The externally fired closed-cycle gas turbine is one of the earliest concepts and was tested even before the creation of direct combustion gas turbine power plants. This technology, coal-fired in a closed cycle, has a high reliability and a long lifetime of the plant, except for some minor problems such as gas leaks or the lubrication system. However, since the performance of gas turbines depends heavily on the turbine inlet temperature, and the component that supply the heat to the cycle (heat exchanger, solar receiver etc.) will remain the key element for their success [107].

Regarding the use of an unfired micro gas turbine, an example of an unconventional application in CSP plants is shown in *Figure 19* below. The CSP plant layout is composed of the following parts: solar collection system, (solar tower, receiver, and heliostats field), micro gas turbine engine (compressor, turbine, recuperator, generator, and inverter), TES, consisting of high temperature (HT) and low temperature (LT) tanks and heat exchanger, the pressure regulation and the management systems and the heat ejector. Cycle starts when the air at point 1 is compressed and flows into the recuperator (point 2) where it is preheated by the air outcoming the turbine. It enters the solar receiver where is heated up; the pressure regulation system works precisely to keep constant this value (point 3) at almost 850°C [108] (dashed line indicates the link between the pressure regulation system and that point). The air is sent to the TES (point 4), where the management system and a valve manages the percentage of the mass flow rate that must across the heat exchanger or directly flows in the turbine. That regulation allows to control the turbine inlet temperature, point 5 in the figure, adapting the power produced by the micro gas turbine to that of the electric grid. Therefore, the air expands and passes through the regenerator (point 6), then into the heat ejector (point 9), to set the air at the initial temperature, and finally the cycle restarts. The pressure regulation system includes high pressure (HP) and low pressure (LP) tanks, an auxiliary compressor, some valves, and acts varying the cycle base (point 1) air pressure; if the receiver incoming thermal power increases (due the reflected irradiance) the pressure is increased, sending air form the HP thank at point 8 to the main cycle, vice versa, air is flown from point 7 into LP tank.

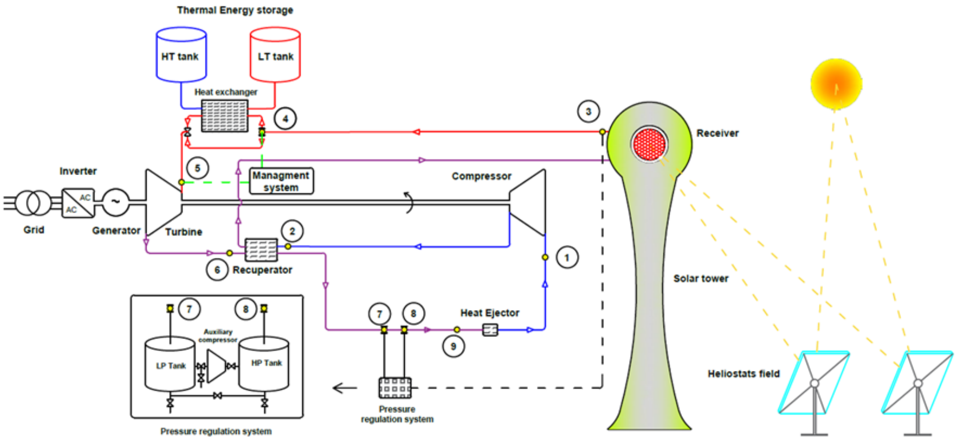

Figure 19: An example of unconventional application in CSP plants

Parabolic dish collector systems are point-focusing CSP technologies typically designed for small-to-moderate capacity applications, of the order of few kilowatts. They are suitable for remote power needs, in rural areas and isolated locations. Moreover, their high modularity makes possible an easy deployment connecting several dishes together in case of higher capacity needs [109]. The parabolic dish solar concentrator system mainly consists of base support, concave dish frame, reflecting sheets, sun-tracking system and engine conversion unit. This point-focusing technology has an average optical efficiency between 0.90 and 0.93 and a concentration ratio between 2,000 and 5,000 suns [110]. Solar dish size is limited by material constraints, and the largest practical dishes are normally around 10 m in diameter and a generating thermal capacity between 10 kW_{th} and 25 kW_{th}, although larger or smaller individual dishes have been constructed [111]. The operative temperature of the receiver, depending on the technology and material constraints, is between 750 °C and 1,000 °C. Research on the energy conversion unit has been mainly focused on Stirling cycle [112], although other cycles have strong potential in flexible polygeneration like the Joule-Brayton cycle. In fact, Brayton technology was tested by first time in a parabolic dish by NASA in the 1980's. This study aimed at developing an alternative to photovoltaic for high density power generation in space [113]. Since then research on dish-Brayton has continuously growing up and addressed topics such as thermodynamic analysis and optimization of regenerative dish-Brayton [114] [115] and specific assessment using micro-gas turbines as as energy conversion unit for the Brayton cycle [116]. These investigations on dish- micro gas turbine mainly cover specific numerical tools for designing small (3 to 35 kW_e) systems [117] on-design and off-design thermodynamic modelling [118] [119] design tools for control strategies [120], and technoeconomic assessment of dish- micro gas turbines. Comparison between dish-Stirling systems in terms of levelized cost of electricity (LCoE) concludes that micro gas turbines allow a cost reduction of 7 c€ kWh_e^{-1} [121]. Besides evaluation of intercooled, reheated and combined configurations using open recuperative twin-shaft Brayton cycle with solar dish indicates that intercooled configuration produces the greatest specific net power output and has the highest thermal efficiency, followed by the combined and reheated cases [122]. Additional cost reduction has been pursued by boost system performance using Ceramic Solar Micro Gas Turbine capable to operate at turbine inlet temperature up to 1,100 °C. A yearly sun-to-electric efficiency as high as 26.48% has been reported using this concept [123]. Off-the-shelf turbochargers has also been proposed as the micro-turbine for a recuperated solar-dish Brayton cycle in order to minimize costs due to turbochargers availability in the vehicle industry [124] later investigated on a recuperated solar dish Brayton cycle together with solar receiver having TES based on phase change material [125]. Demonstration projects on solar dish-micro gas turbines provided a unit cost of 3262 € kW_e^{-1} for the solar-only operation, and this cost can be influenced by the installation site [126], or the potential market [127]. The installed cost is actually still close to that of the solar dish-Stirling, that is 3947 € kW_e^{-1}, and it is in any case higher than the photovoltaic one (1965 € kW_e^{-1}). However, LCoE for dish- micro gas turbine systems can achieve 11.3 c€ kWh^{-1}, in South Africa in some market condition, which is comparable to PV (~10 c€ kWh^{-1}) [128]. Le Roux and Meyer claimed a solar-to-mechanical efficiency of up to 12% using a standard off-the-shelf turbocharger. The authors justify this low efficiency when compared to other solar technologies to the selected turbocharger, which has not been properly optimized to this application [129].

New advances in radial turbomachinery and high-speed electric motors might indeed bring an original and reliable approach of Brayton cycles on CSP. Decoupled radial turbomachines [130], powered by their own electric machines would solve to some extent the coupling problem to the solar receiver. In addition, the use of turbocharger technology can reduce the cost through utilizing massively produced parts. The use of decoupled radial turbomachines allows for tailored design of compressor and turbine wheels what ensures components efficiencies around 80% for design point conditions [131]. The absence of a mechanical linkage between compressor and turbine favors the operation of both machines closer to their corresponding design points and reduces the time-lag and the duration of transient events what has a positive impact into power cycle efficiency. Furthermore, higher efficiency can be obtained for decoupled compressors rather than for standard radial compressors based on the fact that undesirable heat transfer effects from the turbine side will not apply [132]. This concept reduces turbomachinery time lag that occurs during turbine acceleration, which has an impact on compressor boosting. Replacing mechanical linkage between compressor and turbine by independent electric control allows to store energy for fast transient response and also to optimize independently the design of compressor and turbine wheels [133]. As an inherent characteristic of this concept, higher conversion efficiencies than the ones found for conventional radial machines are expected, mainly under transient events, due to no matching restrictions and tailored turbomachinery design for CSP. Beyond mechanical efficiency, decouple turbomachinery allows new configurations in solar dishes that might optimize weights distribution and mechanical stresses.

Micro Gas Turbines / High Temperature Heat Storage

Micro gas turbines / high temperature heat storage combination *(Figure 20)* was investigated with electrical heated thermal storage to increase the flexibility of the storage system and to allow for a constant outlet temperature independent from the load level of the storage system. High temperature heat storage with temperatures up to 1000 °C is meant to be used in such a combination. The heat storage would be charged with surplus electricity and unloaded when electricity prices are high.

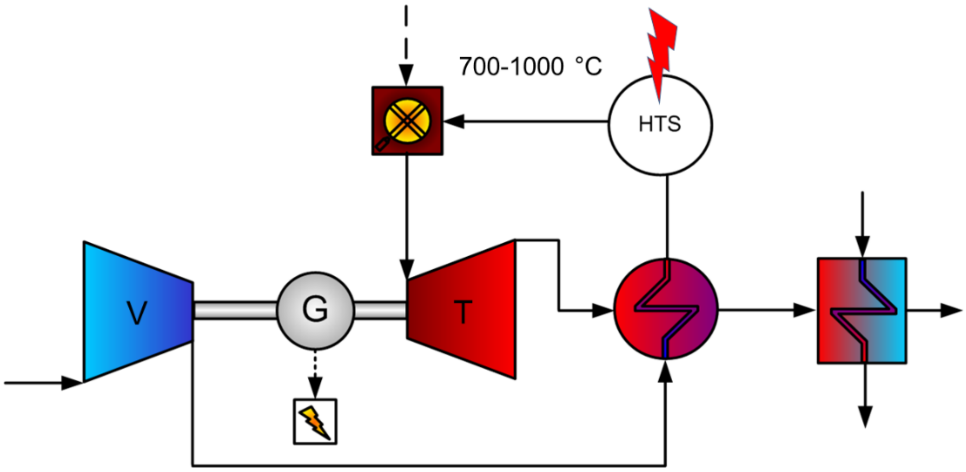

Figure 20: Micro gas turbines / high temperature heat storage combination

In such a system the combustion chamber is the most effected part, as it has to cope with very high inlet temperatures and ensure stable combustion for very small temperature gaps between combustor inlet and outlet. In a similar arrangement the electrical heat storage could be replaced by a solar heat source.

Thermochemical storage with micro gas turbines

A zero-carbon thermochemical energy storage technology that uses an micro gas turbines as core component is the have been developed by Redoxblox. To charge the RedoxBlox system, electricity is used to resistively heat a packed bed of magnesium manganese oxide pellets to 1000–1500 °C, whereupon the pellets undergo a highly endothermal chemical reaction that releases oxygen gas and stores the heat in the form of chemical energy and sensible heat. To discharge the system, pressurized air from the compressor section of a gas turbine generator is passed through the pellet bed, which consumes oxygen from the air, reverses the reaction, and releases heat to the oxygen-depleted air. The hot compressed air is then delivered to the expander section of the gas turbine to generate electricity. Like conventional gas turbine generators, the compressor and expander share a single shaft; however, instead of using the combustion of a fossil fuel to provide the heat—RedoxBlox's system uses the zero-carbon oxidation reaction of its energy storage material. Alternatively, the RedoxBlox energy storage module can deliver high temperature, zero-emission heat for industrial applications by passing low-pressure air through the pellet bed and directing the heat for industrial processing.

The RedoxBlox reversible reduction and oxidation (redox) energy storage reactions are as follows:

- Reduction (charge): $\mathrm{MgMnO3(s)} + \mathrm{heat} \rightarrow \mathrm{MgMnO2(s)} + \mathrm{12O2(g)}$
- Oxidation (discharge): $\mathrm{MgMnO2(s)} + \mathrm{12O2(in\ air)} \rightarrow \mathrm{MgMnO3(s)} + \mathrm{heat}$

These reactions allow extremely high energy storage densities of about 2400–2500 MJ/m^3, of which about two-thirds of the energy storage capacity comes from the chemical reaction and about one-third from sensible heat. The energy storage material can tolerate some impurities, which allows it to be produced at low cost from abundant earth materials magnesium oxide and manganese oxide (i.e., there is no need for expensive purification steps).

Charging

The core of the RedoxBlox system *(Figure 21)* consists of a pressure vessel containing a bed of magnesium manganese oxide pellets, electrodes at either end of the bed. To charge, the electrically conductive pellet bed is energized and volumetrically head, while the blower removes pure oxygen gas liberated from the chemical reduction of the magnesium manganese oxide pellets as they absorb heat. The heating rate of the pellets can be varied, so long as they reach the fully charged temperature within the allotted charge cycle time, which enables the ability to provide grid support services during charging. At full charge, oxygen gas production ceases and electrical heating is cut off. During both charging and standby modes, the air loop originating at the compressor section of the gas turbine generator is closed.

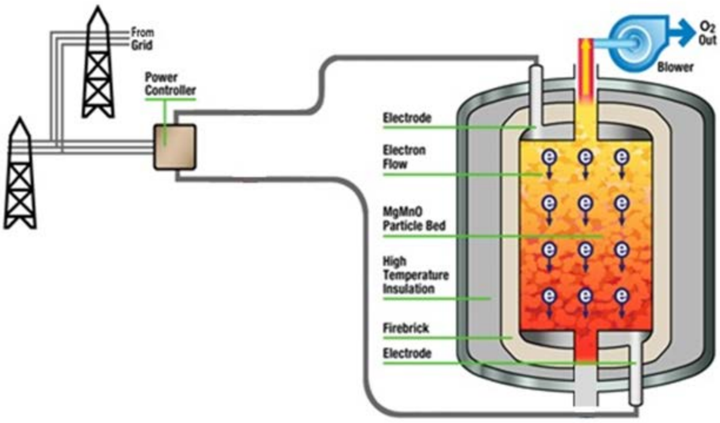

Figure 21: RedoxBlox system Charging Phase
©Redoxblox Inc.

Discharge

The compressor section of the gas turbine generator delivers pressurized air (5-20 bar) to the steel vessel containing the bed of pelletized magnesium manganese oxide energy storage material, whereupon oxygen from the air is consumed by the material and heat is released to the oxygen-depleted air. The hot air is then fed to the expander section of the gas turbine generator, where it provides the mechanical power to drive the compressor and electric generator. The operating pressure, temperature, and flow rate of air through the compressor and expander are designed to match commercial-off-the-shelf gas turbine generators in order to minimize conversion costs and technical risk. As such, the operating pressure of the containment vessel is determined by the specific gas turbine generator model used. During discharge, the oxygen blower shown in the picture above does not operate. Conceptually, RedoxBlox energy storage modules are best suited as a retrofit for gas turbines with external combustors (silo-type). Improved performance is expected for fully integrated (gas turbine-storage) designs, particularly well-suited for retrofitting combined cycle power plants, where the complete topping cycle is available for retrofit.

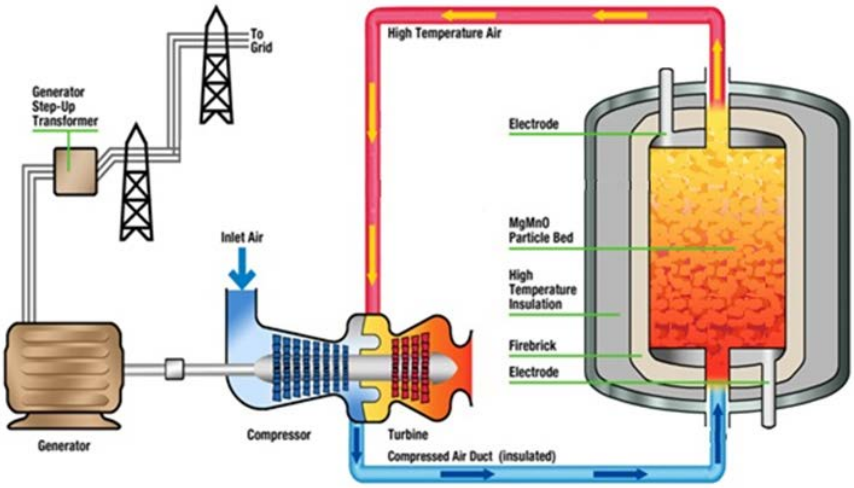

Figure 22: RedoxBlox system Discharging Phase
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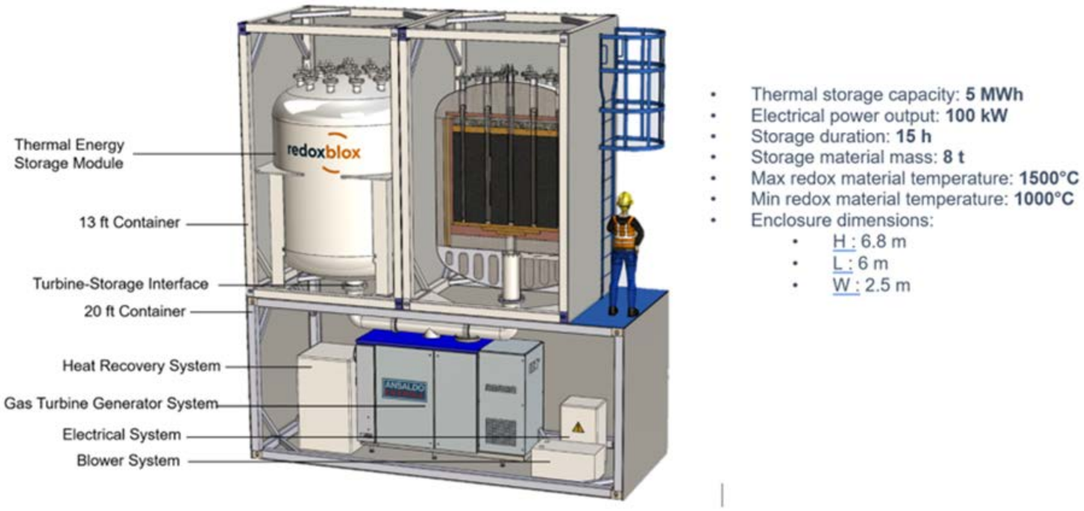
The heat of the hot gases released by the micro gas turbines can be transferred to any fluid for any industrial/ domestic use.



- Thermal storage capacity: **5 MWh**
- Electrical power output: **100 kW**
- Storage duration: **15 h**
- Storage material mass: **8 t**
- Max redox material temperature: **1500°C**
- Min redox material temperature: **1000°C**
- Enclosure dimensions:
  - H : 6.8 m
  - L : 6 m
  - W : 2.5 m

Figure 23 RedoxBlox system overview
© Redoxblox Inc.

EMGT/fuel cell combination

EMGT/fuel cell combination was built in some prototypes during the first years of 2000. Fuel cell types in this context were solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC). Relative to a standard micro gas turbines with recuperation were the following differences applied:

- Opening the micro gas turbines process at the position of the combustor
- Replacing the original combustor by:
- One between recuperator and fuel cell with the purpose to heat the fuel cell up to operational temperature during (cold) start up.
- A second combustor between fuel cell and turbine to compensate for heat extraction due to pre-warming the fuel cell during start-up and keep it on a low level during operation to compensate for temperature loss (minimised heat addition during normal operation).
- Replacing existing components to comply with rules and regulations resulting from combining the micro gas turbines with a unit which has to fulfil the Pressure Equipment Directive (i.e., shut off valves, flame and gas sensors etc.).
- Replacing the existing control system to cope with the increased number of components and sensors as well as to match with the control system of the FC.

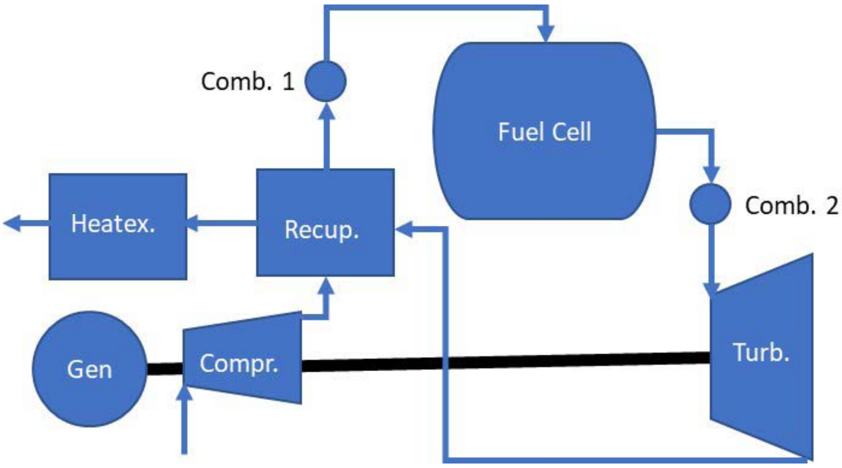


Figure 24: Schematics of a fuel-cell/micro gas turbines integration

SOFC-micro gas turbines hybrid system

SOFC-micro gas turbines hybrid systems are considered promising systems for future generation due to: (i) very high efficiency, (ii) low emissions (also zero emissions depending on the fuel type), (iii) applications in small size units for distributed generation, (iv) applications in cogeneration mode, and (v) low noise operations due to no moving parts in the SOFC. For these reasons, both researchers and industries developed innovative activities on these systems during the past 20-30 years. Although a significant technology improvement has been obtained, at the moment there are some issues not completely solved, such as micro gas turbines/SOFC integration, component costs, SOFC reliability and control system performance to avoid risk situations [134].

The SOFC-based hybrid systems are usually classified in atmospheric and pressurized systems. In atmospheric plants the SOFC is installed downstream of the turbine outlet (for the cathodic side). This configuration, although could reduce the pressurization stress on the cell, is not able to maximize the efficiency potentiality and usually could have some doubtful components about the possible real implementations, such as a too high temperature heat exchanger for the micro gas turbines/SOFC matching. On the other hand, pressurized SOFC-based hybrid plants seem the best solution for exploiting the SOFC efficiency increase due to pressure increase. This configuration seems the most feasible from technology constraints, because this solution does not require any high temperature valves or heat exchanger.

Pressurization is so important in these systems that some researchers proposed an SOFC system pressurized by a turbocharger *(Figure 25)*. This is a reduced cost solution (turbocharger are cheap components due to large mass production) to join the benefits of pressurization avoiding the costs of a microturbine including also power conditioning devices [135]. So, although this solution is not able to maximize the efficiency, it is an effective approach to reduce the plant costs.

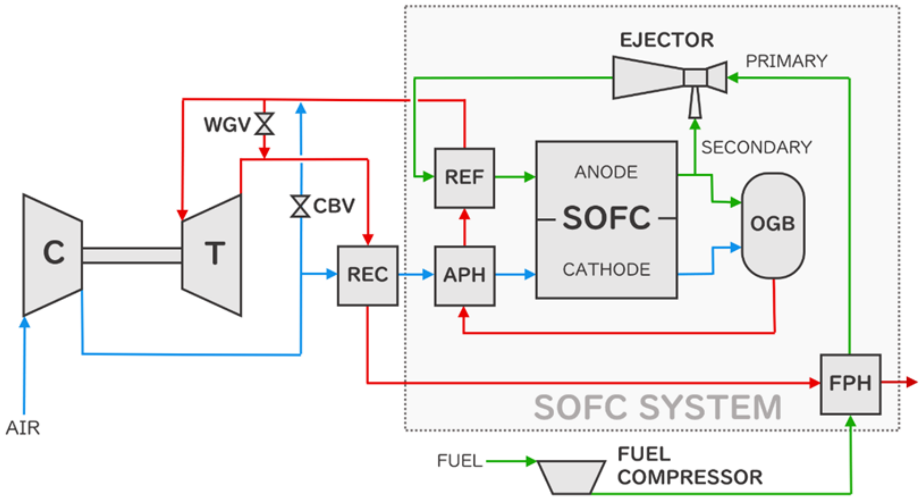


Figure 25: SOFC system pressurized with a turbocharger unit

Basic cycle configuration

The SOFC/ micro gas turbine integration is due to the SOFC outlet temperature condition that is suitable for the coupling with the inlet design temperature of an micro gas turbine unit. Moreover, thanks to the exothermic reactions of the cell, it is possible to exploit this thermal energy for the reforming reactions. Depending on the plant operative conditions it is possible to use the steam reforming technology with these different layouts: (i) an anodic recirculation (managed by a blower or better by an ejector) to provide the thermal energy for the reforming reactions that are endothermic, (ii) a pre-reformer to have an initial fuel conversion for producing an initial amount of hydrogen for the stack, (iii) internal reforming for the further fuel processing (it can be in the direct configuration in case the reforming reactions would be performed directly in the SOFC anodic side).

Another important aspect in these systems is the air pre-heating upstream of the cathodic side. This is necessary because too low temperature condition would freeze the SOFC reactions. The air pre-heating can be obtained with a recuperator (usually this is not enough in planar or flattened-tube cells) or with a cathodic recirculation. The role of the off-gas burner is also important because it can be used to maximize the temperature at the turbine inlet or installed in the cathodic recirculation for pre-heating reasons.

Components

The main component of SOFC hybrid systems is, for sure, the fuel cell. It can be tubular or planar with different geometries. Since the target of the most recent research activities is related to cost decrease, researchers focused special attention on SOFC manufacturing procedures. So, flattened-tube or planar cells are preferred to the tubular SOFCs because of reduced costs in manufacturing. Another important aspect of the SOFCs is related to the operative temperature. While SOFCs working close to 1000°C have demonstrated the highest efficiency potentiality, several activities concentrated attention on low temperature SOFCs for cost decrease reasons.

Considering that the micro gas turbines are fully discussed in other sections, other components to be discussed are: the fuel processing reactors that could be integrated in the SOFC in case of internal reforming technology, blowers or ejectors for the recirculation, the off-gas burner for the fuel components not fully converted in the SOFC, and the power conditioning devices for connecting the SOFC and the micro gas turbines to the local electrical grid.

Demonstration project and commercialised units

Due to the interesting high performance of these innovative systems, several researchers or companies worked on the micro gas turbines/SOFC integration. In details, it is possible to mention the following activities: (i) in 2000 Siemens-Westinghouse tested the first SOFC-based hybrid system in the Irvine University (although the positive results, they were not able to overcome 53% efficiency and the system operations were managed just manually), (ii) Universities and research centres (such as the NETL in the United States [136] performed both simulation and experimental activities on system components or using emulator plants (such as the one at the University of Genoa [137] (iii) Rolls-Royce Fuel Cell Systems developed a prototype of SOFC-based hybrid system trying to decrease the costs avoiding the recuperator (thanks a large application of ejectors), (iv) the Bio-HyPP project coordinated by the DLR produced interesting results in the SOFC/ micro gas turbines coupling using biogas as fuel, (v) in 2019 Mitsubishi presented the first commercial hybrid system based on SOFC technology.

MCFC/Micro Gas Turbines Hybrid System

Despite the fact that SOFC-micro gas turbines hybrid system gained more momentum in terms of system efficiency and commercialization, Molten carbonate fuel cell (MCFC) integrated with micro gas turbine demonstrated a significantly higher efficiency as compared to its standalone MCFC mode. Additionally, systematic way of CO_2 capture in this technology not only makes it economically viable but also environmentally feasible. It is worth mentioning that the captured CO_2 is needed in the inlet air stream to further help in producing carbonate ions needed for MCFC. The enhanced efficiency of the hybrid system lies in the utilization of recovered heat that would otherwise be lost. In order to utilize the waste heat effectively, an optimized heat management appropriate configuration between MCFC and auxiliary power generator is indispensable. The notable auxiliary power generators associated with MCFC are micro gas turbines, general gas turbines and turbo expanders.

Cycle configuration

In general, the hybrid system for fuel cell and gas turbines are segregated into two fundamental layouts I.e., (i) Topping cycle, and (ii) bottoming cycle. In topping cycle, the fuel cell substitutes the combustor while gas turbines acts as balance of plant. Whereas in bottoming cycle, FC uses the exhaust of the gas turbines thereby acting as balance of plant. The simplest configuration of the MCFC-gas tubrines hybrid system is the bottoming cycle or low-pressure configuration. The MCFC-micro gas turbines hybrid systems are classified into two basic configurations based on the heating method of the incoming air that is further expanded in the turbine for subsequent generator power. The configurations are known as indirect and direct heating system as illustrated in Figure X(a), and X(b) below. In the indirect system the heat needed to raise the temperature of the inlet gas to further run the turbine for power generation is normally produced in a catalytic combustor that utilizes the unreacted anodic gas, cathodic gas and unburned fuel. On the other hand, the direct system consists of a combustor that directly burns the gases coming from the anode and cathode and the flue gases are subsequently expanded in the turbine section. The direct heating system is considered as the promising option for increasing the temperature and pressure of an inlet gas due to better heat and system management characteristics.

Components

The components of MCFC-micro gas turbines hybrid systems varies from configuration to configuration. In case of indirect heating system, the major components are high temperature recuperator, low temperature recuperator, heat recovery unit, fuel cells, and gas turbines. Since there is a scarcity of experimental test facilities, it's hard to compile the exact details of the components. However, based on numerical simulations studies available in public domain, variety of components have been incorporated depending on various configuration. When it comes to the recuperators, the number of recuperators has been incorporated in different counts. Normally, one recuperator is needed for anode, one for cathode and one for air to turbine. However, a few studies have considered 2 and 3 recuperators for air to turbines. For indirect heating system the reformer is assumed to internal type.

The cycle configuration of a direct MCFC-gas turbine hybrid system is a bit different from that of indirect configuration. Therefore, the components also vary accordingly. Several numerical studies available in the literature manifested variety of components. The most indispensable component in this configuration are combustor and heat exchangers. Normally, one combustor for anode and cathode exhaust gas are installed while a few studies also installed extra combustor for additional natural gas supply in order to meet the designated turbine inlet temperature for the gas turbines. Additionally, the count for heat exchanger is also of varied nature. The widely considered number of heat exchangers are one for each electrode i.e., anode and cathode air. In some studies, multiple heat exchanger for anode has also been suggested. Moreover, heat exchanger for fuel also have been incorporated widely. The reforming mechanism in this configuration is found to be external type.

Demonstration project and commercialised units

Since the MCFC-micro technology was a bit more developed (in 2000-2010 years) than the SOFC-micro gas turbines one, different researchers and companies started to develop system prototypes for a future commercialization. Special attention has to be devoted to the prototype by Ansaldo fuel cells that was based on a 100 kW MCFC connected and pressurized by a T100 microturbine [138]. Although the work obtained important results [139], the activity was terminated before reaching the market. This was due to the integration complexity (too much recirculation to be managed in off-design and dynamic conditions) and to the overtaking of the development status of SOFC-micro gas turbines systems.

A second important activity to be cited was performed by Toyota. In details, at the Aichi World Exposition (Japan, 2005), Toyota demonstrated the generation with an MCFC/micro gas turbines hybrid plant reaching 52% efficiency. In this system a 358 kW MCFC was coupled with a 50 kW recuperated microturbine for different days [140].

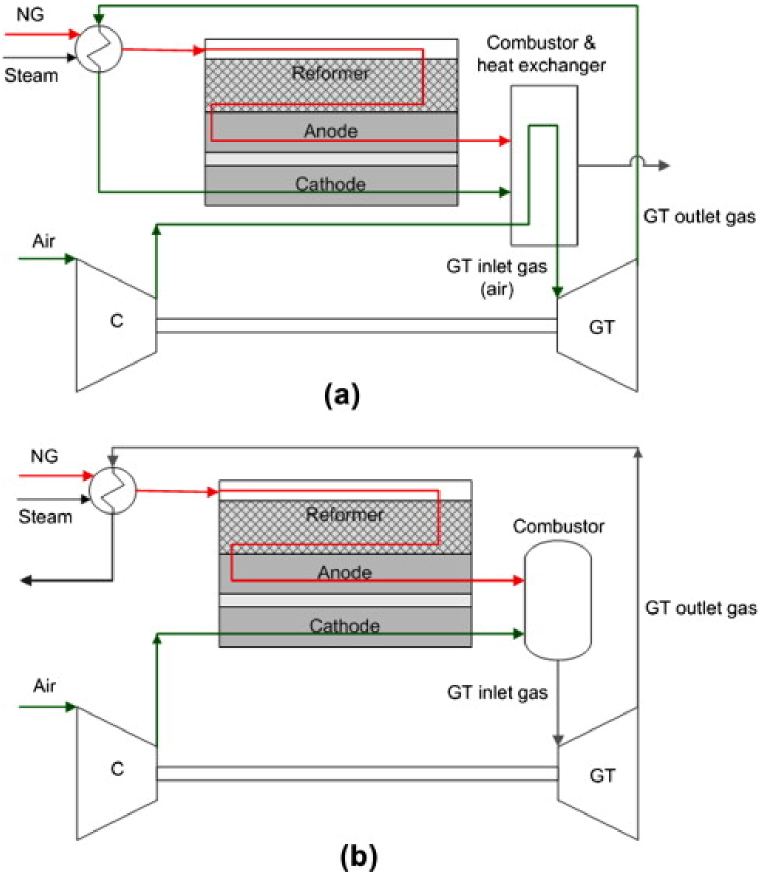


Figure 26: Schematics of two different configurations of MCFC-micro gas turbines

The chemical process / micro gas turbines integration was conceptionally developed for a formaldehyde production plant. The plant required energy for a blower supplying air to the process while at the same time releasing exhaust gas at and elevated temperature and without any further use. An energy balance showed that by slightly pressurizing the process it was possible to:

- Increase the production capacity of the plant due to higher mass flow
- Improving the energy efficiency by eliminating the extra power demand of the blower

In the application evaluated was the pressure ratio limited to 1.2 resulting minimal surplus power and given the available turbine inlet temperature.

A generic setup of such process is represented in *Figure 27*.

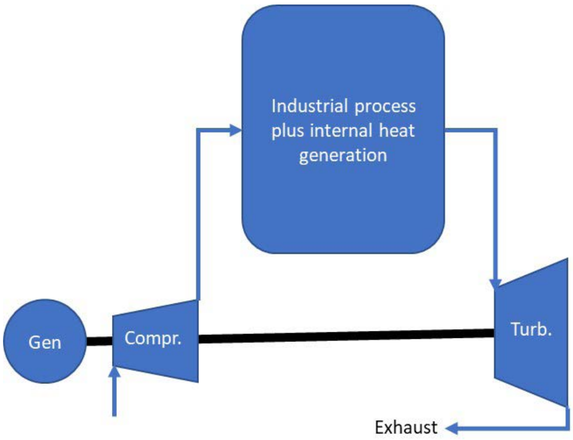


Figure 27: Generic setup of a gas turbine/industrial process integration in normal operation

It needs to be noted that additional components might be necessary to be added to allow for heating up of the process, supplementary heat addition to increase the power output etc.

3. Conclusion and future directions

Among different topics, a small but important portion of this report covered the perspective of policy and regulatory frameworks pertinent to DES. There are still several obstacles slowing down the development of distributed generation (DG) technologies despite higher general attention to DES at different policy levels in local, governmental, and European scales. Such obstacles can include, but not limited to, the regulatory variations in connection requirements (including technical ones) to distribution networks across countries, limited financial incentives, and lack of fair business models between different stakeholders (e.g., for small but important services between DSOs and DES owners). Therefore, there is a need for faster and better policy alignments, and implementation of regulatory frameworks to ensure the growth of DES and the transition towards a more sustainable energy system.

Irrespective of these non-technical obstacles, the market for DES has been experiencing a steady increase, also with respect to gas turbine installations over the years. However, this market has not been so easy for gas turbines below certain sizes. More specifically, for systems with sizes of less than one megawatt, reciprocating engines have been more competitive with many more installations, as compared to gas turbines. Fuel cells are the other technologies that are expected to make the market even more competitive in a similar range (i.e., sizes below 1 MW). Drop in capital costs and increased technological maturity of fuel cell technology are among the parameters that can impact the competitiveness of gas turbines in the DES market. Despite these challenges, specifically in lower sizes, new opportunities and emerging markets and services can arise. Such opportunities include the utilisation of alternative and unconventional fuels, smart grids, microgrids, and small-scale air and road transport. Continued progress and advancements driven by different stakeholders within the gas turbine community will improve the market share of small-scale gas turbines for DES applications. An important general aspect also applicable in the context of DES is enhancing the performance of smaller machines like micro gas turbines via increasing the firing temperature, or through the integrated and optimised design of various components. In such classes, the recuperator is still a critical component that strongly affects the system's performance. Design optimisation efforts should be continued to find the best compromise between heat transfer, compactness, and pressure losses to maximise the machine's overall efficiency.

Part-load operations also became a key factor negatively affecting the integral efficiency of the system. Therefore, improving the efficiency of the compressor and turbine in part-load conditions along with the design point is essential. In such a prevailing operational regime, another approach to improve the part-load performance is to increase modularisation. Here, one unit can be operating at optimal design load, while other units be shut off. This enables higher component and integral efficiencies resulting in lower operational costs, but certainly results in additional capital costs.

We should also remember that DES configurations are becoming increasingly complex as we shift towards hybrid multi-generation systems. Traditionally, there is a predominance to size and control the operation based on the electrical demand, where thermal generation is seen as a bonus (like a by-product) to the electrical generation (as the main product). As opposed to this view, research advancements are needed for sizing the unit with considerations of both (or multi) energetic demands following a balanced strategy that prioritises all products to increase the integral efficiency of the system.

As per applications, gas turbine technology is well-established in small to medium industrial plants and larger buildings with high heat demand, such as hospitals, hotels, and swimming pools. In most applications, these gas turbines are still operated with fossil fuels like natural gas. However, due to their potential for fuel flexibility, these systems would be well-suited to work with renewable fuels like biogas, hydrogen, and syngas. This report also presented new promising applications for gas turbines in DES, such as gas turbine integration with TES, concentrated solar gas turbines, and hybrid fuel cell and micro gas turbine configurations.

Despite the fierce technological competition, (micro-) gas turbines can play a pivotal role in DES. Their integration in DES applications can be facilitated through enhanced performance over the entire operating window, improved fuel flexibility, better compliance to improve interoperability (within different parts of energy systems and infrastructure), development into new and emerging markets, and services (e.g., stabilising the power grid).

In addition to all these aspect for improvement of gas turbines in a DES context, several activities should be carried out in the future aiming to identify open issues and gaps to close from the perspective of the end-users. For this purpose, and starting in 2024, the ETN Global DES Working Group will collect the users' needs and requirements by carrying out interviews with relevant stakeholders. Based on the outcomes of this new initiative, follow-up activities will be proposed to the members of ETN Global.

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