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Review

The Role of Micro Gas Turbines in Energy Transition

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Abstract: In the progressively rising decentralized energy market, micro gas turbines (MGT) are seen with great potential owing to their low emissions, fuel flexibility, and low maintenance. The current transformation in the landscape of electricity supply with an increasing share of fluctuant renewable energy resources and increasing complexity requires a reliable and energy-efficient power generation source to support the grid. In this scenario, small-scale power plants that are constructed based on micro gas turbines with up to 250 kW power range can play a substantial role in meeting the challenges of the modern electricity grid. Micro gas turbines provide a reliable and cost-effective power source with a quick load-following ability which can respond to demand peaks and compensate for intermittent renewable sources when they are not available. MGT units can work as a system together with renewables, or function as a stand-alone unit in off-grid operations. The features of micro gas turbines are compatible with the energy transition that is the carbon-free modern energy grid. The technology underlying MGTs offer hybridization with renewable energy sources, flexibility in operations and type of fuel, and promising low emission solutions that align with environmental concerns. However, there is a continuous need to improve energy efficiency with a pressing urge for reducing emissions. This paper provides a review of micro gas turbines' characteristics which promote their role in future power and heat generation systems. A brief overview of the challenges to improving operational flexibility, reliability, and availability of MGTs while maintaining low environmental impact and lowering the costs is presented. A model for an active monitoring and control system of the micro gas turbines is proposed which could improve the reliability of MGT operation in the grid by means of AI methods.

Keywords: micro gas turbine; energy transition; condition monitoring; performance improvement

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1. Introduction

Centralized power generation exploiting fossil fuels or nuclear technology in largescale plants is no longer a vision of the future that climate change scientists, regulators, and growing majorities of voters approve of. Distributed energy generation (DEG) facilitates the use of different energy sources that are available for customers to choose from and install in small increments. These units provide the required power to meet the end-user demand. Distributed power is generated at or near the point of use with technologies such as gas turbines, fuel cells, diesel and gas reciprocating engines, solar panels, and wind turbines.

There are significant advantages that are associated with the replacement of centralized energy generation plants with a DEG system. The main environmental benefit of distributed systems is the reduction in carbon dioxide emissions from fossil fuels that is replaced by renewable sources such as solar power and wind. Long-term cost savings can be achieved as DEGs enable the governments and decision-smakers in the utility division to avoid considerable capital investments in new fossil fuel-based power plants and build transmission and distribution infrastructure. DEG plants are situated near commercial, industrial, and residential users, which results in a reduction of energy losses that may occur due to inefficient power lines. Moreover, the short distance between generation and consumption enables access to small heat sources/sinks and provides the opportunity for exploiting waste heat for cooling/heating purposes which is scarcely feasible in centralized power generation. DEG's location flexibility has a great positive effect on energy prices as well [1]. The distributed system provides diverse options for types of energy resources and fuels employing different technologies. Therefore, there is no need for a certain type of fuel more than others which can reduce fuel prices for customers [2].

Besides the economical benefits, DEGs have positive technical impacts on system operation such as improving voltage profile and power quality [3]. They can reduce the distribution networks' power losses by providing sufficient power relative to demand and reducing unnecessary power flow inside the transmission network [4].

DEGs can harness energy through a combined heat and power system, which might otherwise be wasted. Combined heat and power (CHP) units are more economical than conventional power generation systems [5]. They exploit waste heat for heating, cooling, or improving their efficiency by generating more power, which is not feasible in the sole utilization of centralized power generation [1].

The European Union (EU) energy system is shifting towards decentralized power and heat generation due to the availability of a vast share of renewable sources [6]. With an increasing number of units deploying solar, wind, and hydropower and small-scaled CHP plants connecting to the grid, the role of the utilities and independent power producers is evolving. Figure 1 displays the share of DEG in global power generation for the years 2000 and 2020 according to [7].

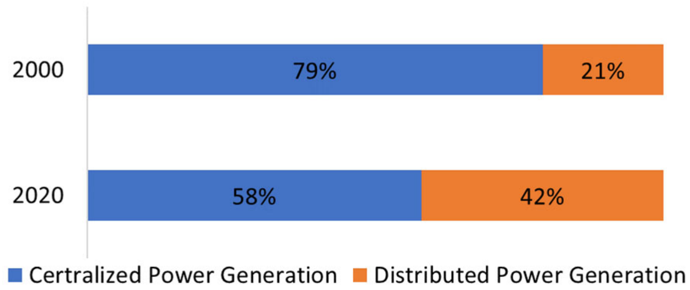


Figure 1. Share of DEG in the global power generation.

The current shift in the power generation industry towards more renewable and distributed generation strengthens the need for reliable and efficient small-scale dispatchable supply units. With increasing utilization of intermittent renewables such as solar and wind, a larger fluctuation in electricity input to the grid is introduced because of their non-dispatchable nature. They provide fluctuating and uncertain power outputs that are specific to certain locations. Therefore, supplementary systems and hybrid technologies are required to secure power outputs and meet demands. Micro gas turbines can provide fast and reliable power to compensate for renewable oscillations and guarantee smooth outputs to meet energy demands.

A decentralized power generation scenario integrating MGTs with wind turbines, solar systems, biomass plants, fuel cells, and energy storage would provide a secure, stable, efficient, economical, and environmentally friendly energy production system, close to consumption points, which provides the heat and electricity without major transportation and conversion losses [6]. Figure 2 gives an overview of different technologies in DEG and the position of MGT in the mix. It is worthful to note that the fuel flexibility of MGTs provides carbon-free and carbon-neutral choices of fuel such as hydrogen and biogas, which is not shown in the figure.

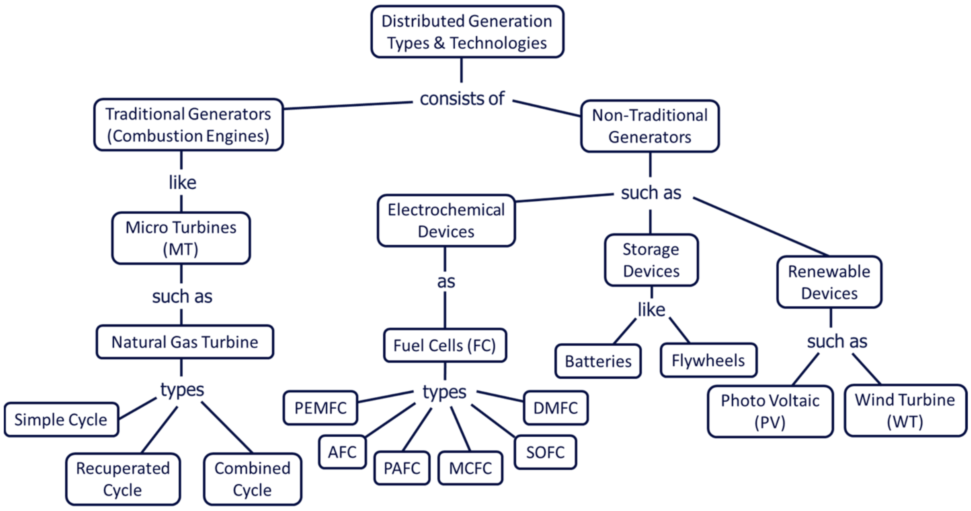


Figure 2. Distributed generation types and technologies [8].

MGTs have reliable operations [9] and have well-known technology, can start up rapidly, and require less maintenance due to their simple design [10]. An economic lifetime of up to 80,000 operating hours can be achieved in micro gas turbines with a maintenance interval of 4000–8000 h of operation, which is longer than most internal combustion engines [11]. They have been commonly used in many engineering fields and have already been proven to be reliable, work satisfactorily [9], and are suitable for integration with other systems or as a subsystem in a larger energy system [6].

They have lower capital costs than other DEG technologies with the potential for low-cost mass production [12]. Opportunities to utilize waste fuels (such as agricultural residues or organic waste) and energy recovery are other economic advantages of utilizing MGT systems. MGTs are very efficient with an overall efficiency (electricity + heat) up to 90% in case of using an economizer and have lower emissions compared to large-scale gas turbines [6].

Micro gas turbines that are used in co-generative applications have proven to be a promising technical solution for high-efficiency energy conversion. These comprise both combined heat and power and combined cooling/heating and power (CCHP). Exhaust gas out of the turbine in MGTs can be employed directly for heating or be recovered in a heat recovery unit (CHP application) or an absorption chiller (CCHP application) for cooling purposes. The utilization of MGTs in cogeneration mode improves their overall efficiency and operational flexibility, which makes them an attractive choice for applications that require a range of electrical to thermal output ratios [13]. These characteristics of MGTs have made them a transition technology for the EU's ambitious 2030 energy targets and a prime mover of the future for competitive, secure, and sustainable micro-scale poly-generation [6].

The structure of the paper is as follows: first, the environmental reasons that shape the energy roadmap are discussed in Section 2. In that section, the shift of power generation from a centralized to a decentralized scheme is reviewed. In Section 3 the position of heat and power cogeneration units in a decentralized system is discussed. Section 4 presents the micro gas turbine structure and its advantages over the competitors, followed by a brief history of MGT development in Section 5. Lastly, the challenges of improving MGT performance and suggestions for promoting them are provided by proposing an active condition monitoring and control system in Section 6.

2. Energy Policy

In this section, a brief review of the evolution of the electricity generation scheme is presented. The energy policy in the current world and associated studies are reviewed to illustrate the potential of MGTs in the near-future power generation system.

2.1. Climate Change and the Future of the Energy Framework

It is common knowledge that greenhouse gas (GHG) emissions are the main reason for the abnormal increase in the average surface temperature of the earth. National and international political bodies are discussing the "energy problem" and are pursuing possible solutions. The United Nations Framework Convention on Climate Change "COP21 Agreement" has given strength to the policies on climate change and the energy transition to a low-carbon energy scheme. In October 2014, the European Union agreed on vision 2030, to further increase the penetration of renewable energy technologies and improve the overall energy efficiency of electricity production with a reduction of GHG down to 40% (from 1990 levels), along with an ambitious target to reduce GHG by 95% until 2050 [14]. The vision is to keep the global temperature increase to well below 2 °C and pursue efforts to keep it to 1.5 °C [15].

According to the International Energy Agency projections, the average CO_2 intensity of electricity production needs to fall from 411 g per kilowatt-hour (g/kWh) in 2015 to 15 g/kWh by 2050 to achieve the goal of limiting the global increase in temperatures below 2 °C. While many studies confirm the feasibility of the goal, the development of a clear strategy and designing technical infrastructure is essential to achieve the new power market [16].

The key targets of the EU for 2030 were [15]:

- At least 40% reduction in greenhouse gas emissions (from 1990 levels), by decreasing emissions and increasing removals;
- At least 32.5% improvement in energy efficiency;
- At least 32% share for renewable energy.

As a part of the European Green Deal, in September 2020 the European Commission proposed to raise the 2030 greenhouse gas emission reduction target, to at least 55% compared to 1990 [15]. In December 2011, the European Commission communicated on the topic "Energy Roadmap 2050". The EU is committed to reducing greenhouse gas emissions to 80–95% below 1990 levels, aiming to be climate-neutral (with net-zero GHG emissions) by 2050. Figure 3 depicts the EU energy targets. These targets aim to help the EU achieve a more competitive, secure, and sustainable energy system.

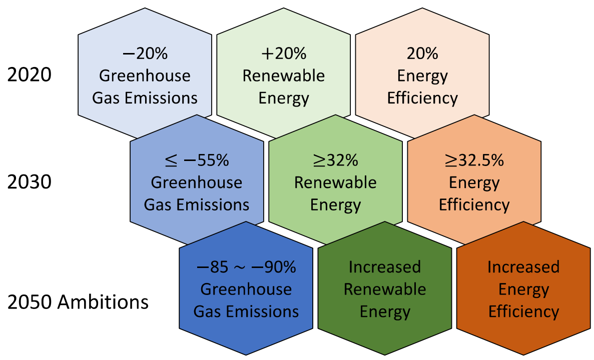


Figure 3. EU targets for renewable energy technologies penetration with GHG reduction [14] modified with new proposed targets [15].

One of the main challenges of the energy roadmap is the volatile feed-in from the solar and wind power plants. Electricity generation from wind and solar sources represents fluctuations that are inherited from their intermittent nature which affects the stability and reliability of the grid and could cause issues to a secure energy supply. This necessitates the development of energy backup systems to compensate for the fluctuations, consisting of storage methods for periods of oversupply, and flexible power production stations in episodes of low inputs from the renewable sources [17,18].

To provide secure, reliable, clean, and sustainable energy, a broad portfolio of energy conversion and storage technologies will be required. This is likely to include nuclear power generation, concentrated-solar power plants, and hydrogen power plants, along with new technologies improving overall energy efficiency, as well as continued use of fossil fuels, ultimately with carbon capture and storage [19]. Due to the inevitable phases of low energy input from renewables, thermal power plants will be suitable for load control and backup power if sufficient storage capabilities are not available. The fossil power stations will be utilized only for the periods when wind and sun are absent. Utilizing large thermal power plants for standby functions will be accompanied by considerable operation costs.

Currently, the energy supplement in the world is dominated by fossil fuels and there are numerous functioning power plants and substantial fuel resources available. Therefore, even though they are the undesired sources for long-term ambitions of GHG reduction, it seems impossible for them to be phased out by the mid-century. According to recent research, 37% of the global CO_2 emissions are attributed to some industrial sectors such as iron, steel, and cement sectors. Therefore, fossil fuel-based power plants are difficult to eliminate [20]. Consequently, it is important to develop technologies that permit fossil-fueled plants to operate as low-emission power generators.

There are two main concepts to capture CO_2 from fossil fuel power plants: pre-combustion (CO_2 extraction from the synfuel) and post-combustion (CO_2 capture from exhaust gas) [21]. The CO_2 may be stored and disposed of in a distant geological storage site after capture. However, there is public and political opposition against geological storage sites on land in several European countries [22]. The carbon capture and storage (CCS) process costs about 10 to 14% of the production efficiency of a fossil-fuel plant [21] which is a considerable fraction of the whole establishment.

Another fuel resource for power plants is biomass, the most important renewable energy source which covered nearly 60% of renewable-based power production in Europe in 2016 [23]. On average, in industrialized countries, biomass contributes about 9–13% to the total energy supplies, but in developing countries, the proportion is less than 7% [21]. The electricity and heat producers of future power production systems must be able to function with carbon-neutral or carbon-free fuels, such as biofuels, hydrogen, or ammonia. While redeveloping large-scale fuel-flexible power plants is expensive, building small-scale power generation technologies which can operate with a range of fuels are technically and economically feasible.

It is anticipated that the future structure of power generation will appear in a similar layout as depicted in Figure 4. The power supply system will be a combination of big and small generators, where the small ones supply local power demands, and the big stations are for the system backup and are equipped with carbon capture and storage.

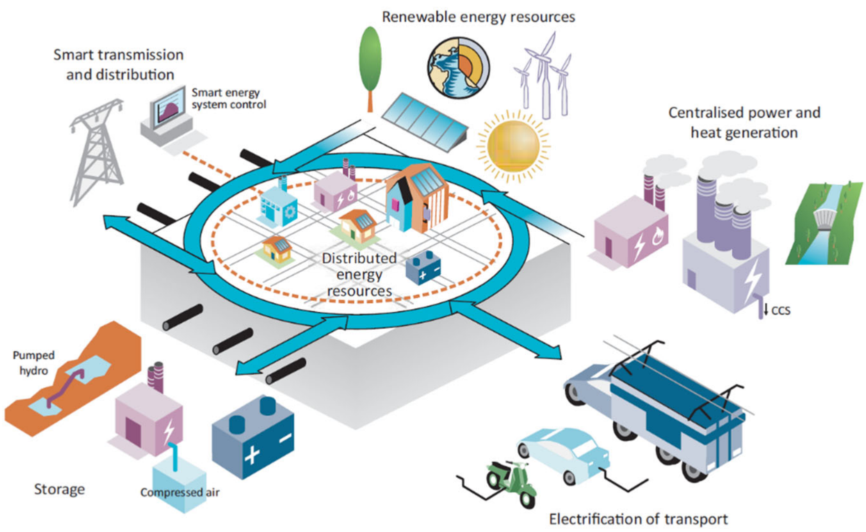


Figure 4. The integrated and intelligent electricity system of the future [24].

In the new scheme of power generation, the local power supply is called a microgrid (MG) which bind together to organize the local balance of the power system. If a microgrid cannot achieve the balance, then it will get power from the neighbor microgrid or the strong backup system to assure constant frequency [25].

Figure 4 shows a “smart grid”, a combination of local networks with active consumers and small storage, a strong backbone network, and powerful generators. The buildings, as one of the main consumers of electricity in today’s platform, will play an active role in the system, where they become flexible storage or even a supplier for the grid [26].

2.2. Option for Future Decentralized Microgrid Energy Structures

Microgrids are a group of interconnected loads and distributed energy resources within defined electrical boundaries, which act as a single controllable entity with respect to the grid. It can be connected and disconnected from the grid since it is capable of operating in both grid-connected and islanded modes [14]. Microgrids have been researched for decades [27], however, increasing penetration of distributed energy resources (DERs) into the existing power sector is raising the motive to develop advanced technologies for MG power generation units [28]. Besides the global warming effects, the increasing penetration of DER is attributed to fossil fuel shortage and political instability in the major energy-supplying countries [14]. Moreover, production costs for developing distributed energy resources declined due to technological improvements, hence the renewable energy sector has witnessed a boom in the past decade [14]. In the decentralized scheme, low power loss in the transportation of electricity due to the proximity of the production unit to the consumer is another attractive feature promoting it. Advanced MG systems will improve energy security and provide power that is efficient, reliable, and clean [18,29]. The international energy policies toward less GHG emissions are other key drivers for promoting renewable energy targets and DER, changing the MG role from a secondary energy source to a primary energy supply [27].

The rapidly increasing trend of microgrid integration into the electricity grid presents technical barriers and problems such as voltage stability, distribution system operation, control, and protection [30]. Technical challenges have been investigated for over a decade, and now can offer a stable and smoother energy supply [14]. However, the operation and maintenance of MG power units show improvement prospects for more reliable power generation.

2.3. Changing Role of Electric Power

The main sectors of the final energy consumption of EU-27 in 2018 were in the areas of residential (26.1%), transport (30.5%), and industry (25.8%) [31]. Figure 5 illustrates the share of different sectors in final energy consumption for EU-27 countries in 2018. The urbanization of the world is in progress which has a significant influence on energy demand. In developing countries, today more than 50% of the population are living in urban areas (Table 1), whereas in industrialized regions such as Europe already 77.5% has been reached. In industrialized countries, the electrification rate is more than 95% in urban areas (100% in the EU), but it is only about 60 to 70% in rural areas. One can say that urbanization is linked to electrification [21].

Table 1. Urbanization rate in percent of the total population in developing countries and industrialized countries [20].

	1950	1960	1970	1980	1990	2000	2010	2020	2030	2040
DC	18.0	21.7	25.3	29.6	35.1	40.2	45.3	50.5	56.0	61.6
IC	52.5	58.7	64.6	68.8	71.2	73.1	75.0	77.5	80.6	83.5

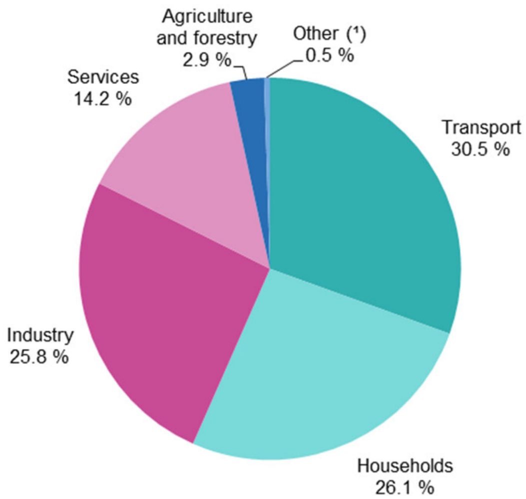


Figure 5. Final energy consumption by sector, EU-27, 2018 [31].

Electricity represents clean energy and is the ideal form of supply for densely populated urban areas. The building sector is crucial for achieving the EU's energy and environmental goals. The EU "directive on the energy performance of buildings" provides the guidelines for the reduction of total energy consumption in the residential sector in the EU [32]. The aim of the directive is a "low-energy building" with a very high energy performance which improves the higher life quality of residents with additional economic advantages [33].

The microgrid concept for urban and residential households is a suitable solution for an increasing urban population, especially for operation in cogeneration mode [33]. A combined heat and power (CHP) generation mode of microgrids is an efficient solution for recovering the residual heat in the power generation unit to be exploited in proper form by the end-user. In centralized power generation mode, a part of the electrical power that is delivered to the residential sector is transformed and expended for heating or cooling purposes. Cogeneration units in DEG networks avoid inefficient heat to power and again power to heat conversion deficiencies.

3. Cogeneration of Heat and Power

Providing electricity and heat at the demanded location is the main purpose of the energy market. Even in today's predominantly centralized power generation structure, heat generation is decentralized and produced near the end-user because of the high loss in heat distribution over long distances. The current shift in the electricity market towards a decentralized generation network corresponds with the current distributed heat generation scheme, particularly, a decentralized co-generation of power and heat will fulfill the new energy market structure.

Small-scale energy conversion units that can provide both electricity and heat to the customer are assumed to be the main elements of microgrids that correspond to the urban sector. Besides a reliable power supply, a micro-CHP unit provides the opportunity to exploit the remaining energy from the electricity generation process for heating or even cooling purposes, thus maximizing the level of fuel utilization and potentially decreasing carbon and air pollutant emissions by improving energy efficiency.

The European Union Cogeneration Directive sets down goals for "good quality" CHP to be a part of the delivered electricity [34,35]. However, these goals are yet to be reached. In the United States (U.S.), many states realized the value of DER and CHP to mitigate emissions and fuel consumption to fulfill environmental targets as well as achieve economic benefits [36]. Studies focusing on CHP systems and their role in meeting GHG reduction goals were investigated in different states of the U.S. [37,38], different countries in Europe [34,35,39,40], as well as on a global scale [41]. It was concluded through these efforts that CHP is promoted as an economical and energy-efficient option for reducing air emissions, mitigating GHG emissions, and reducing reliance on grid electricity and hence enabling peak load shaving [42]. Industrial applications of CHP have been around for decades, converting 80 percent or more of the input fuel into an adequate type of energy, producing electricity and thermal energy onsite [43]. New thermally-driven cooling technologies are being developed and demonstrated that can potentially utilize the CHP heat output effectively for cooling purposes [43].

The U.S. Environmental Protection Agency (EPA) defines CHP as an efficient and clean approach for generating electricity and useful thermal energy from a single fuel source [20]. A typical CHP system operates by generating hot water or steam, deploying the recovered waste heat, and therefore, fulfilling the end-user's heat demand. The provided heat can also be directed to an absorption chiller where it can provide cooling which is called combined cooling, heating, and power.

With climate change and increasing temperature, the heating demand for the residential sector of energy consumers will decrease. Conversely, the cooling desires of household and commercial units will grow in which the CCHP mode of cogeneration will be desired. In today's marketplace, there is a variety of cooling technology options for the cogeneration of cooling, heating, and power. Absorption chillers are the most common technology that can be installed to utilize heat output to produce cooling [43].

The U.S. EPA CHP partnership gathered data and promoted the development of CHP in the industrial and commercial sectors in the U.S. and provided a thorough summary of the available existing prime mover technologies to drive a CHP system and a review of CHP systems around the world [44]. According to this effort, small CHP technologies or so-called micro-CHP technologies are the proper options for distributed generation (DG) [44]. Typically, DG is defined as power generation that is smaller than 50 MW with the unit output being used either on-site or close to where it is produced.

In one study, researchers evaluated a wide range of DG units to determine the potential for cooling, heating, and power in the U.S. industrial sector [43]. The study was focused on units by the year 2002, and included reciprocating engines, industrial turbines, microturbines, combined-cycle turbines, and fuel cells. The application of these units for electricity generation as well as cogeneration with heat and cooling were considered. The outcome of this research showed substantial market potential for CHP units in the U.S. industrial sector [43]. Market estimates show that almost three-quarters (73%) of the power market potential is for straight CHP applications, of which only one-third of the potential was available and in use in 2022 [43]. CHP with an absorber represents 15 percent of the potential, serving industries with substantial cooling demand, including the chemical and petroleum industries. The sole power generations showed only 11 percent of market potential. The research clearly shows the promising future for cogeneration on small scales in the U.S. [43].

In the same research, the authors investigated the market potential of CHP technologies variations by the size of the generating unit. In 2002, the U.S. market for small-size engines (under 1 MW) was dominated by reciprocating engines. Their combination of high efficiency and low installed cost made them a perfect choice. In the mid-range (1–20 MW), however, turbines were the prime movers, due to the large concentration of CHP-compatible sites in this size range. In large power sizes (20–50 MW), turbines offer economic potential with large combined cycles. The combined cycle applications were attractive in industries (such as steel) with relatively low steam demands.

The details of the investigation provide more insight into this market analysis with aspects such as the type of technology depicted in Figure 6. The analysis showed the dominance of micro gas turbines, industrial turbines, and reciprocating engines in 2002's CHP market. At that time, analyses showed that an adaptation of many high-efficiency features to turbine technology was to be expected which will take CHP's market share from other technologies, and even improve reciprocating engines. The same conclusion was made regarding the growing market for micro gas turbines in [45]. The reason behind this was that the electrical efficiency improvements that were projected for micro and industrial turbines were much greater than those that were projected for reciprocating engines [43].

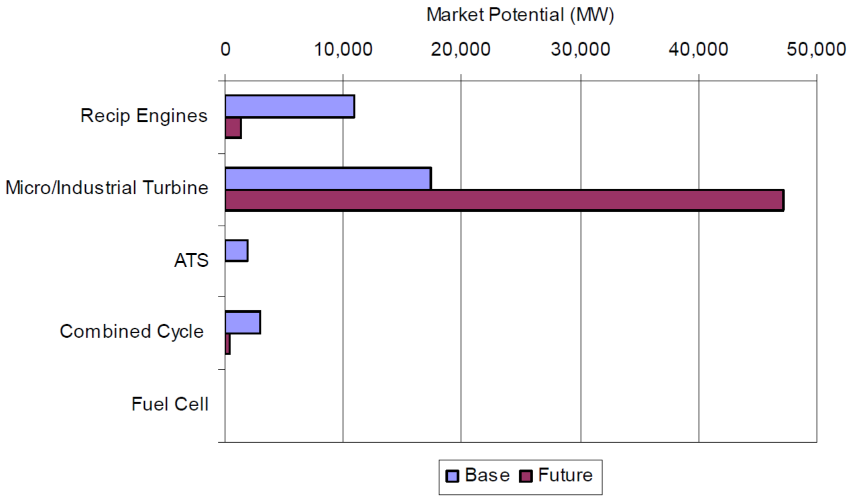


Figure 6. Market potential by technology, base data were collected in 2002 [43].

The investigations in [43] also showed that the turbine CHP market will expand and microturbines will take over in the under 1 MW applications, and larger (over 1 MW) turbines benefit from improved electrical efficiency and lower capital cost per unit power output [43]. Moreover, the low noise levels and NOx emissions of the micro gas turbines will be their other advantages over the rest of micro-CHP technologies [20]. The results are illustrated in Figure 7, showing the role of micro gas turbines with cogeneration capabilities in the future of energy production.

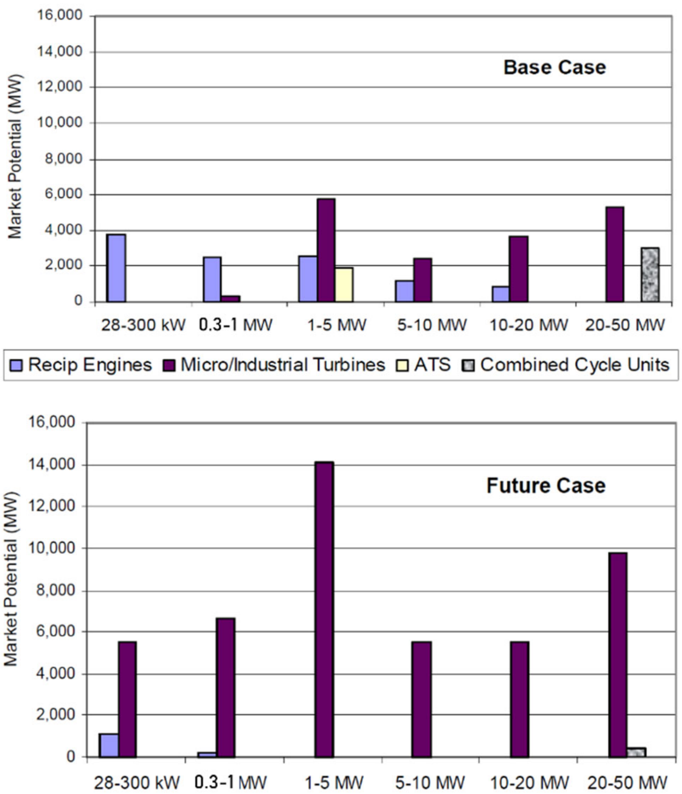


Figure 7. CHP technology market potential by unit size, base data is collected in 2002 [43].

To attain the high efficiency and reliable performance of MGTs as a CHP unit in future microgrids, further research, and development (R&D) is needed to promote these technologies and compete with more conventional options. CHP and thermal cooling technologies share the need for lower costs, increased efficiency, reduced maintenance, greater reliability, and lower emissions. While these needs vary by technology, the overall goal should be to support the industry in developing lower-cost CHP packages that improve industrial energy efficiency and reduce operating costs.

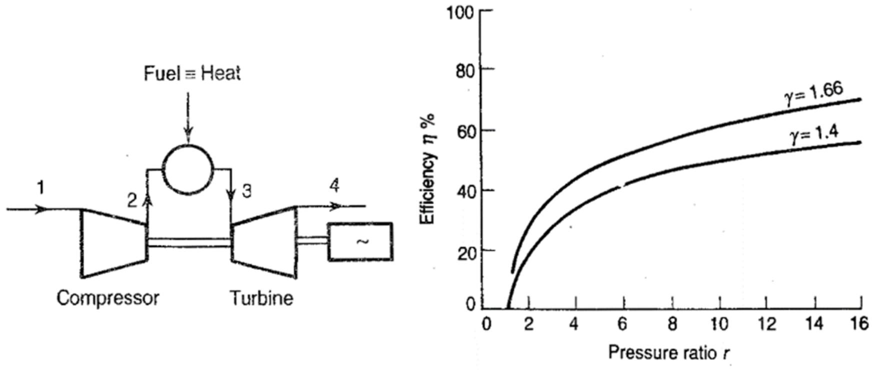
Currently, utilities and consumers are encouraged to move towards decentralized market structures and integrate with distributed small generators. With increasing power and heat demand due to the expansion of the urban sector, CHP technologies in compliance with microgrid networks will gain the most attention. As the study showed, micro gas turbines with cogeneration mode show the most potential as an economically beneficial market.

4. Micro Gas Turbines

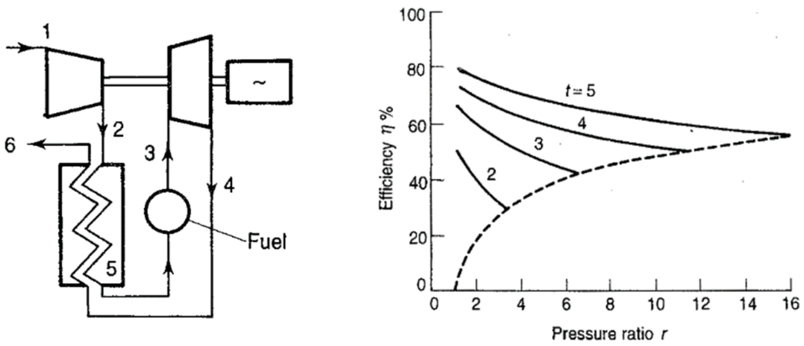
Micro gas turbines are basically small gas turbines with a power output range of 30 to 250 kW, operating on the same principle as open-cycle gas turbines. The setup consists of a compressor, a combustion chamber, and a turbine, forming a basic Brayton cycle. In this cycle, the air is compressed by the compressor then receives thermal energy by added fuel that is passing through the combustion chamber, thus leaving with a high-temperature gas. The high-pressure and-temperature gas enters the turbine where it expands and provides power to drive the compressor and the electric generator. For typical power ratings, the optimum rotational speed in micro gas turbines is between 60,000 to 120,000 rpm, a pressure ratio of 2:1 to 5:1, and turbine inlet temperature up to 1000 °C [46].

The single-shaft structure is the most common configuration of micro gas turbines [47], however, there are dual-shaft MGTs that are available in the market [46]. Single-stage centrifugal compressor and radial turbine are employed, which are manufacturing choices for compact sizes. Typical MGT employs a permanent magnet generator that is capable of compensating for the high rotational speed of MGTs which varies during the operation period [46]. Furthermore, microturbines usually employ variable-speed alternators generating a very high-frequency alternating current which must be first rectified and then converted to alternating current (AC) to match the required supply frequency [46].

The net electrical efficiency of a micro gas turbine in a basic Brayton cycle is usually low and about 17% [48] due to the small cycle pressure ratio. Moreover, the power output is also limited to turbine material constraints and cost limitations of the implementation of internal cooling systems on small scales such as micro gas turbines. The overall efficiency of MGTs is improved by preheating the compressed air to reduce fuel consumption. This pre-heating occurs in an air–air heat exchanger element called a recuperator that is placed in the way of exhaust hot gases to facilitate heat transfer between the hot exhaust gas and cold compressed air. The recuperator is, therefore, a vital element that increases the cycle efficiency to acceptable ranges. Fuel consumption in cycles that are equipped with recuperators is reduced and electrical efficiency of up to 30% can be achieved [48]. Furthermore, the low-pressure ratio in micro gas turbine cycles is advantageous for regenerative cycles since these cycles operate with higher efficiency in lower pressure ratios, as shown in Figure 8 [28]. For co-generation mode, the remaining heat in exhaust gas leaving the recuperator is transferred through another heat exchanger to provide hot water for heating purposes or be exploited in a chiller for cooling applications.



(**a**)



(**b**)

Figure 8. Cycle efficiency based on pressure ratio, (**a**) simple cycle, (**b**) regenerative cycle [49]. In schematic diagrams of gas turbine cycles in (**a**,**b**), the numbered locations are: 1. engine inlet, 2. compressor outlet, 3. combustor outlet, 4, turbine outlet. additional locations in (**b**): 5. recuperator outlet—cold-side and 6. recuperator outlet—hot-side. In efficiency diagram of (**b**) t is defined as ration of turbine inlet temperature to engine inlet temperature.

Figure 9 shows the simplified scheme of a micro gas turbine cycle arrangement with a recuperator and an economizer for co-generation.

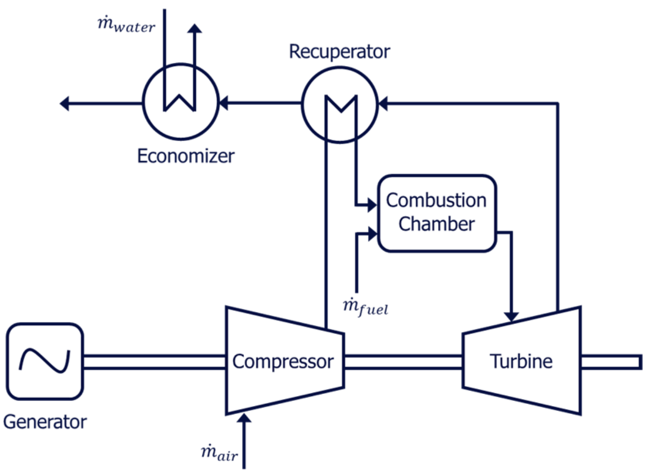


Figure 9. Typical MGT cycle with recuperator and economizer for combined heat and power generations.

An important advantage of micro gas turbines over other heat engines for decentralized power generation is their fuel flexibility, ranging from natural gas, diesel, liquefied petroleum gas (LPG), and hydrogen, to waste- and biomass-derived fuels. In fact, MGTs can operate with fuels with low heating value without engine derating [6]. The combustion systems of micro gas turbines can also be designed in such a way that they can easily burn fuels with lower octane numbers as well as heavier hydrocarbon components [50]. The same is true for fuels containing hydrogen [51].

Relative to other technologies for small-scale power generation, micro gas turbines offer several advantages, including compact size, light weight, and low noise compared to other internal combustion engines (ICE) with similar power output ranges. They can be installed on-site with limited space. They have a small number of moving parts with small inertia (unlike large gas turbines with large inertia).

Another important advantage of micro gas turbines, over other ICEs such as reciprocating engines, is MGTs' low emissions [20]. Table 2 presents the baseload emissions for different micro gas turbine systems.

Table 2. Baseload emissions for different micro gas turbine systems [21].

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

A comprehensive survey was performed and reported in [20] and modified by Reinert [52] investigating the performance indicators, cost, and advantages of different cogeneration technologies towards one another. A summary of this investigation is reported in Tables 3 and 4, showing the advantages of MGT over the other technologies of the same power range.

Table 3. Comparison of CHP technologies: sizing, cost, and performance parameters—part 1 [20,52].

Technology		Steam Turbine	Gas Turbine	Microturbine
Capacity	MW	0.5 to several hundred	0.5–300	0.03–0.25
Power efficiency	Based on HHV	5–40+%	24–36%	25–35%
Overall efficiency	Based on HHV	near 80%	66–71%	63–85%
Typical power–heat ratio	-	0.07–0.1	0.6–1.1	0.5–0.7
Part-load	-	ok	poor	ok
CHP installed costs	$/kWe	670–1100	1200–3300	2500–4300
O&M cost	$/kWe	0.006–0.01	0.009–0.013	0.009–0.013
Availability		72–99%	93–96%	98–99%
Hours to overhauls		>50,000	25,000–50,000	40,000–80,000
Start-up time		1 h–1 day	10 min–1 h	60 s
Fuels		all	natural gas, synthetic gas, landfill gas, fuel oils	natural gas, biogas, sour gas, liquid fuels
Noise		high	moderate	moderate
Uses of thermal output		process steam, district heating, hot water, chilled water	direct heat, hot water, LP & HP steam	direct heat, hot water, chiller
Power density	kW/m^2	>100	20–500	5–70
NOx	lb/MMBtU	gas 0.1–0.2 wood 0.2–0.5 coal 0.3–1.2	0.036–0.05	0.015–0.036
NOx	lb/MWh total output	gas 0.4–0.8 wood 0.9–1.4 coal 1.2–5.0	0.52–1.31	0.14–0.49

Table 3. *Cont.*

Technology	Steam Turbine	Gas Turbine	Microturbine
Advantages	high overall efficiency, high temperature, high-quality heat any type of fuel may be used ability to meet more than one site heat grade requirement long working life and high reliability power–heat ratio can be varied	high reliability low emissions high-grade heat available no cooling required high-cost effectiveness	small number of moving parts compact size and light weight low emissions no cooling required
Disadvantages	slow start-up low power to heat ratio	require high-pressure gas or in-house gas compressor poor efficiency at low loading output falls as ambient temperature rises	high costs relatively low mechanical efficiency limited to lower temperature cogeneration applications

Table 4. Comparison of CHP technologies: sizing, cost, and performance parameters—part 2 [20,52].

Technology		Reciprocating Engine	Fuel Cell
Capacity	MW	0.005–10	200–2.8 commercial CHP
Power efficiency	Based on HHV	27–41%	30–63%
Overall efficiency	Based on HHV	77–80%	55–80%
Typical power–heat ratio	-	0.5–1.2	1–2
Part-load	-	ok	good
CHP installed costs	$/kWe	1500–29,000	5000–6500
O&M cost	$/kWe	0.009–0.025	0.032–0.038
Availability		96–98%	>95%
Hours to overhauls		30,000–60,000	32,000–64,000
Start-up time		10 s	3 h–2 days
Fuels		natural gas, biogas, propane, LPG, sour gas, industrial waste gas, manufactured gas	hydrogen, natural gas, propane, methanol
Noise		high	low
Uses of thermal output		space heating, hot water, cooling, LP steam	hot water, LP-HP steam
Power density	kW/m^2	35–50	5–20
NOx	lb/MMBtU	0.013 rich burn 3-way cat. 0.17 lean burn	0.0025–0.0040
NOx	lb/MWh total output	0.06 rich burn 3-way cat. 0.8 lean burn	0.011–0.016
Advantages		high power efficiency with part-load operational flexibility fast start-up relatively low investment cost can be used in standalone mode and have good load following capability can be overhauled on-site with normal operators operate on low-pressure gas	low emissions low noise high efficiency good part-load behavior low maintenance
Disadvantages		low electrical efficiency	high costs low durability fuels requiring processing unless pure hydrogen is used start-up time

5. History

The development of micro gas turbines started in the early 1950s when most of the research was driven by the automotive industry viewing the possibility of using microturbines as alternatives to reciprocating piston engines [53]. This initiative was because of micro gas turbines' advantages regarding low emissions and operational and fuel flexibility. The technology became more suitable for utilization by introducing permanent magnets as high-speed generators in the early 1980s [54]. Permanent magnet generators are rotating electric machines in which permanent magnets prepare field excitation [46]. These high-speed generators offer small size, light weight, high reliability, high efficiency, and low maintenance which make them an advantageous choice to integrate with micro gas turbines [54]. However, even with permanent magnet generators, the technology of a hybrid-electric drivetrain was not mature enough and, therefore, microturbines did not achieve great success in the automotive segment [55].

The interest in micro gas turbines increased in the late 1980s and accelerated in the 1990s due to increased market interest in distributed power generation [55]. In the late 1990s, the market for hybrid vehicles started to expand and they also began to increase interest in micro gas turbines, integrating them with electric motors to generate propulsion force [46].

The deregulation of the electricity market began in late 1970s in the United States and several countries in Europe [46,56]. Breaking the monopoly in the electricity generation sector and increasing the expansion of decentralized power generation was another reason for the promotion of micro gas turbines. Micro gas turbines began to attract attention from the research and development sector due to their potential and place in the new decentralized electricity market. In the 1980s, a 50-kW gas turbine with a heat recovery system for cogeneration was under development under the Advanced Energy System (AES) program [46]. The program, however, was abandoned in the 1990s due to the high final cost of the product [46].

A Capstone turbine was incorporated in 1988 as NoMac Energy Systems started developing the micro gas turbine concept in the late 1980s, began field testing in 1997 for a 24-kW engine, and introduced the commercial product to the market in 1998 [53]. In the late 1990s micro gas turbines found acceptance in large quantities in the distributed power generation field [57]. In 2000, the state-of-the-art MGTs had electrical efficiency between 23% to 30% with an overall efficiency in cogeneration mode between 65% and 75% [58].

Other companies that were based in the United States, England, and Sweden have been introduced since then which offer a variety of power outputs to be installed in microgrids or for implementation in hybrid cars. Among these companies are Elliott Energy Systems, Capstone, Aurelia, Turbec (a spin-off of Volvo which was later purchased by Ansaldo Energia), AlliedSignal, Browman Power, and ABB Distributed Generation in a joint venture with Volvo Aero Corporation. A summary of the main features of MGTs in leading manufacturers is presented in Table 5 and a more elaborated history of micro gas turbine development could be found in [59].

Table 5. Technical characteristics of leading microturbine manufacturers [46].

Model	Manufacturers	Power Output	Set	Total Efficiency [1]	PR	TIT	NS
		kW		%	-	°C	rpm
-	AlliedSignal	75	single shaft	30 (HHV)	3.8	871	85,000
TA45	Elliott Energy System	45	single shaft	30	-	871	-
TA80	Elliott Energy System	80	single shaft	30	-	871	68,000
TA200	Elliott Energy System	200	single shaft	30	-	871	43,000
C30	Capstone	30	single shaft	28	-	871	96,000
C65	Capstone	65	single shaft	29	-	871	85,000
C200 HP	Capstone	200	single shaft	33	-	870	45,000
-	Power WorksTM	70	dual shaft	30 (HHV)	3	704	-
T100	Turbec	100	single shaft	30	4.5	950	70,000

[1] Total efficiency is calculated based on LHV unless it is specified otherwise.

6. Challenges and Opportunities

The MGT industry currently faces new challenges of increasing operational flexibility, reducing operating costs, and improving reliability and availability while mitigating environmental impact. The main concern when it comes to distributed generation is the ability to maintain performance and high availability while minimizing the operation and maintenance costs [60].

One of the main challenges that is raised in the MGT is the overall efficiency of the cycle in the operation range, including design point and part-load conditions. Even though cogeneration applications of MGT lead to higher thermodynamic efficiencies, there are episodes of poor matching between heat and power demand, which indicates that further investigations are required to attain more efficient performance schemes [60]. With an increasing number of passive houses, demand for heating will decrease which raises more challenges in the techno-economic aspects of MGT technology. However, the decrease of heat demand due to a paradigm shift in the structure of residential units and global warming effects will increase cooling demand, in which case the cooling application of MGTs will become more prevalent. For such applications, developing technologies for a more sophisticated operation of a micro gas turbine in cogeneration mode is essential.

Although performance improvements of gas turbine engines have been a subject of interest for decades, some features of micro gas turbines make them dissimilar to larger engines in several operating and system characteristics:

- The simple cycle form of micro gas turbines is less efficient than larger industrial gas turbines since the cycle pressure ratio in MGTs is considerably lower. The small size constraint in micro gas turbines imposes manufacturing complications to potential improvements of cycle parameters, such as pressure ratio and turbine inlet temperature. A recuperator helps with compensating for these deficiencies in MGT cycles which makes them an essential element of micro gas turbines, unlike large-scale engines.
- Micro gas turbines operate at significantly higher shaft speeds. With a smaller size, typical problems such as tip supersonic speeds or mechanical limits are delayed to even higher rotational speeds. Therefore, micro gas turbines can operate at speeds above 100,000 rpm whereas a larger gas turbine will typically operate in the range of 3000 to 20,000 rpm [6]. Moreover, with compensating generators connected to MGTs, the rotational speed can vary according to power demand, unlike most large-scale turbines that remain at a constant speed. This alteration of rotational speed leads to different optimization practices for performance improvements.
- MGT cycles operate with lower pressure ratios (2~5) and turbine inlet temperatures (typically less than 1000 °C) which make the part-load operation span of these systems different from large-scale gas turbines (with pressure ratios up to 25 and turbine inlet temperatures up to 1700 °C). The span of cycle parameter variations, especially with altering rotational speed, is smaller compared to large-scale gas turbines.
- Considering the low-pressure ratio as well as the small volumetric flow and small power rating, a single-stage radial compressor and turbine are usually used. Both components have different operational behavior from axial versions, which is the common configuration that is implemented in large-scale engines.
- If the micro gas turbine operates as a CHP or CCHP unit, the system includes a second heat exchanger that uses the remaining exhaust thermal energy after the recuperator. The available exhaust gas, typically around 300 °C, provides energy for water and space heating, cooling systems such as absorption chillers, and process heat applications. The implementation of an economizer adds more application flexibility as well as constraints to the cycle.
- The fuel flexibility of MGTs, although having environmental and financial advantages, poses certain challenges to MGT design and operation. For conventional cycles, the low calorific value of the fuels requires the implementation of a larger volumetric flow of fuel to achieve the design turbine inlet temperature. This will affect the original matching point with the compressor. Considering the common turbine

choking condition, the larger fuel flow rate results in lower demand for air from the compressor and, in general, an increase in compressor back-pressure and, therefore, lowering the surge margin [6]. On the other hand, a high air–fuel ratio within the primary combustion zone is required for achieving low emission levels at full-load conditions. Lean premix operation requires a large amount of air to be thoroughly mixed with fuel before combustion. This premixing of air and fuel enables clean combustion to occur at a relatively low temperature that is tolerated in uncooled turbines [61]. Therefore, some operational limitations are imposed on the fuel–air flow ratio considering the type of fuel that is injected into the engine.

All the above-mentioned aspects of MGTs lead to a different practice to improve theirs in comparison with large-scale gas turbines. MGTs and the MGT cycles need further development towards [6]:

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

Improving the efficiency, flexibility, and reliability of micro gas turbines could be pursued by two approaches:

- component level
- system level

The main components of the engine, namely the compressor, recuperator, combustor, and turbine, show great potential for improvement in MGTs. The recuperator is responsible for a significant fraction of the electrical efficiency; therefore, its performance and limitations are additional parameters to be considered for improvements. On the other hand, the materials that are used in recuperators impose limitations on flow temperature at the turbine outlet (and the turbine inlet and hence the power output). Focusing on new designs and materials for recuperators could contribute to the efficiency of MGTs.

MGTs as a backup for the renewable-dominant power system of the future will operate in part-load conditions as frequently as in full-load conditions. Therefore, it is essential to improve the efficiency of the compressor and turbine in off-design conditions along with the design point.

Combustion in MGTs occurs with lower equivalence ratios; the typical fuel–air ratio in MGTs is about an order of magnitude smaller than large-scale gas turbines. This means that the variation of flow properties in the flue gas in the case of replacing natural gas with hydrogen is small and, therefore, fewer complications are to be expected. The reason behind this is that flue gas properties of pure methane and pure hydrogen combustion diverge from each other as the equivalence ratio increases, yet in very lean combustions the difference is small. Focusing on hydrogen-driven MGTs will lead to building dispatchable units with zero carbon dioxide emissions. While fuel flexibility is an established advantage of MGTs, burning hydrogen and hydrogen-blended fuel is a goal to be accomplished by focusing on new technologies for combustion chambers.

Besides the component improvements, the system level improvements which are associated with the engine cycle and control of its operation could have a significant effect. Although MGTs are designed to run in cogeneration mode, the operation strategy is not mature and works the same as large-scale engines with addendums for cogeneration. The common design philosophy of operation control is based on sole electricity generation with an additional option of heat production. The controller runs the engine by focusing on power output and placing heat demand as the second priority. To improve the performance and operation efficiency of MGTs, it is essential to increase the flexibility of their operation by modifying the control and by setting the same priority for both heat and power generation.

As elaborated in the previous sections, the MGTs' main role in the future power generation industry is to provide support for intermittent renewable energy sources. Therefore, continuously monitoring MGTs' condition is important to maintain a reliable operation and avoid unpredicted shutdowns. Engine online monitoring is essential for tracking key parameters that are linked to the engine's health condition. Deterioration in engine performance has to be detected in the early stages, as well as signs of potential engine faults. Proper measures should be recommended based on the detections to prevent penalties on engine performance or even its life cycle in more severe cases.

A fault refers to a condition of an engine with a change of the form of its component(s) and hence its performance, from its original design or its initial operation. An engine fault can manifest itself by a change of the geometrical characteristics and/or integrity of the material of its parts, such as fouling, corrosion, erosion, etc., in a compressor or turbine. Monitoring the condition of the engine and its performance during operation and analyzing the observations and sensor measurements can help with detecting those possible faults. Engine faults can have other reasons such as bearings' wear, insufficient cooling of bearings, combustor malfunction, etc. Usually, non-performance-based monitoring methods such as vibration and oil samples can help with the detection of these faults.

To properly monitor the health condition of an MGT, an accurate model which represents healthy operation, and a condition monitoring platform that compares the engine and the model outputs are required. A precise computer model of the engine imitating the whole cycle performance in full-load and part-loads must be employed. The healthy engine model could be physics-based [62,63] or data-driven, either way, the accuracy and speed of their prediction are the essential characteristics.

To develop a predictive model of the MGT cycle when a physics-based approach is chosen, a reduced order (0D and in some cases 1D) model is sufficient, as long as the maps and correlations that are implemented inside the components match the behavior of the actual healthy engine. To this end, a generic model of an MGT must be ready which could be tuned and become "adapted" to the actual engine during the first maneuvers of the operation. Once this model is tuned, then it works as a representative of a healthy engine and could be utilized as the core of condition monitoring platform. In [64] a review on cycle modeling of MGTs is presented, and in [63] a full process of accurate MGT model adaptation to experimental data is presented. Figure 10 shows the adaptation process which is titled "learning period". The model should run by the same power setpoint as the actual engine and then the outputs of MGT and the model are compared and used for modifying the model's tuning parameters, which are basically the calibration factors of the maps and correlations. This process will continue until the difference between the engine outputs and model results are closer than acceptable tolerance. If the data-driven approach is chosen for building the model, the process will be replaced by simple data-based model training, by the means of machine learning methods.

After the learning period is completed, the model must be utilized to provide inputs for the condition monitoring platform. In Figure 10, in the section "operation period", a structure for intelligent monitoring and control of MGT is proposed. The structure has three main poles: engine model, condition monitoring, and optimizer. The model is adapted to the healthy engine during the learning period, based on the initial operating hours of the MGT when it was assumed healthy. Then, a condition monitoring platform plays its role, which receives data from the engine as well as the model predictions.

The data-based condition monitoring can help with improving the reliability of the engine and reducing maintenance and operational expenditure by preventing harmful damages to the engine and avoiding unscheduled shutdowns. The advent of Industry 4.0 and the digitalization era provides the infrastructure for online collection and fast analysis of sensors' data to infer the condition of parts of the engine without dismantling the engine or getting direct access to its parts.

Artificial intelligence (AI) has demonstrated a powerful capacity in detecting and diagnosing faults of gas turbine engines [65]. Monitoring through AI is proven to be an effective method for shifting from classical "fail and fix" practices to a "predict and prevent" methodology. Enhanced analytics and AI-enabled algorithms can help identify out-of-band behavior to improve efficiency and help with keeping the balance between energy supply and energy demand. AI techniques are quite useful when the problem is highly non-linear and a functional relationship between inputs and outputs is not easy to set up, or a quick response is required for real-time applications. Since physical problems of gas turbines have nonlinear and multidimensional characteristics, efforts to apply AI to performance prediction and fault detection and diagnosis of gas turbines have increased during the past decade [65,66].

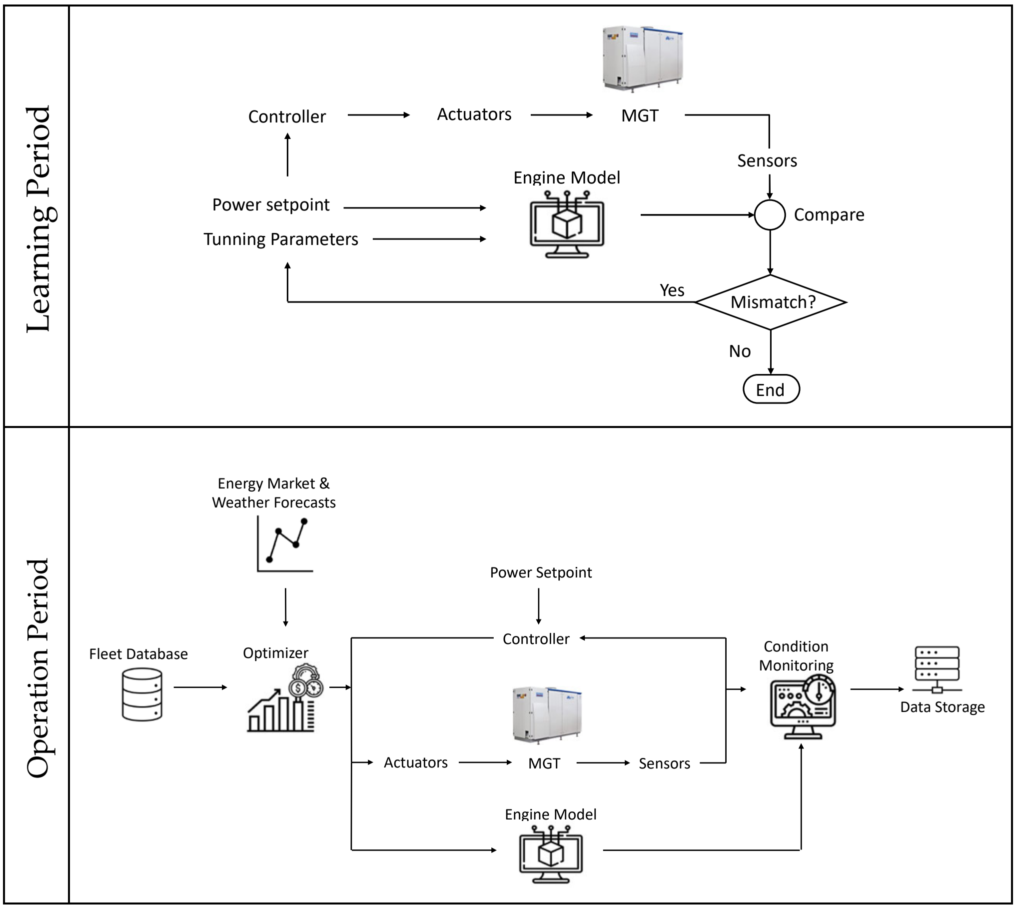


Figure 10. Micro gas turbine fleet control based on online condition monitoring.

The collected data in the condition monitoring platform of Figure 10 will be recorded and analyzed to estimate the health status of the MGT, which could improve the machinery maintenance strategy by employing statistical machine performance data and operational experience and hence prevent unexpected failure in the system. Online condition monitoring helps with predictive model improvements and, therefore, finding more optimized solutions for engine performance, which is the main role of the third pole of the system, the optimizer. Realizing the actual health condition of components of the engine, an adaptive control scheme can be employed to compensate for the effect of deterioration. The component degradation level is assessed by the variations in the available measurements; then the information about engine health conditions is employed to adopt modified control strategies that guarantee a safe operation and limit the reduction in performance efficiency.

The function of the optimizer is tied to the controller of the micro gas turbine. The controller's function is to command the engine to operate with a specific fuel flow rate and specific rotational speed, that generates the demanded power while keeping the engines' components safe. The controller parameters, however, are constant and usually designed based on the engine operating at its absolute healthy status. If the condition monitoring platform could provide information that indicates the engine's deviation from its initial health, these control parameters could be modified by the optimizer and lead to higher efficiency and lifetime of the MGT. This flexibility of operation and increasing efficiency could be enhanced furthermore by adding flexibility to the cogeneration mode, as discussed previously. Inputs from weather and energy market forecast will be also beneficial to find the optimum operational strategy. The weather condition not only affects the fuel prices but also affects the amount and type of demand (i.e., electricity or heat).

It Is useful to put the data from one engine into a database of the fleet of micro gas turbines, where the diagnosis information of each engine could be available for others. The changes in controller parameters and their effect on performance will be useful and provide guidelines. Other than diagnostics of the micro gas turbine, sharing information among the engines could be beneficial for prognostic purposes. In Figure 10, the data from condition monitoring are collected and stored in the fleet database which is called by the optimizer. With a sophisticated infrastructure to organize the data, the prospect of employing more intelligent operation strategies will be increased.

7. Conclusions

Micro gas turbines provide a reliable and cost-effective power source with a quick load-following ability which can respond to demand peaks and compensate for intermittent renewable sources when they are not available. MGT units can work as a system together with renewables, or function as a stand-alone unit in off-grid operations. MGTs are fuel flexible which can offer cost-effective electricity and heat production, especially with fluctuating fuel prices. As a small power plant that is utilized in private households or public buildings, MGTs offer low noise, easy operation, and highly reliable power generation units, which are the most important requirements for decentralized energy systems.

Combined heat and power systems based on MGTs have a higher share than micropower generators in the market due to the decentralized foundation of heat production. Moreover, the cogeneration of heat and power increases thermal energy conversion efficiency and reduces costs.

In this paper, the increasing role of micro gas turbines in the future of energy transition was investigated. The characteristics of micro gas turbines which make them a perfect choice as dispatchable standby unit for a renewable-dominant power generation scheme is reviewed. The challenges and places for further improvements that could accelerate the promotion of micro gas turbine was explained. Finally, a model for an active monitoring and control system of the micro gas turbine was proposed which could benefit from AI techniques to improve the reliability of micro gas turbines.

The continuous development and implementation of diagnostics can significantly reduce both the financial losses that are caused by system breakdown and the costs that are attributed to unnecessary repair and replacement of components. Moreover, the condition monitoring assessments could be provided to an optimizer that changes the operational strategy of the MGT controller, seeking higher efficiencies, a longer lifetime, or both. The integration of MGT cycle data with smart tools based on AI techniques can potentially increase the useful operational hours and thus higher investment returns. Digitalization based on intelligent tools is, therefore, needed to conduct real-time analysis, considering the key parameters such as components' conditions, power demand patterns, and market prices to identify a smart combination and deliver high efficiency from existing installations [60].

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References

1. Alvarado, F.L. Locational Aspects of Distributed Generation. *IEEE Power Eng. Soc. Winter Meeting. Conf. Proc.* **2001**, *1*, 140. [CrossRef]
2. Silvestri, A.; Berizzi, A.; Milano, P. Distributed Generation Planning Using Genetic Algorithms. In *PowerTech Budapest 99. Abstract Records*; IEEE: Piscataway, NJ, USA, 1998; p. 257. [CrossRef]
3. Barker, P.P.; de Mello, R.W. Determining the Impact of Distributed Generation on Power Systems: Part 1—Radial Distribution Systems. In Proceedings of the 2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134), Seattle, WA, USA, 16–20 July 2000; pp. 1645–1656.
4. Generation, A. Dispersed generation impact on distribution networks. *IEEE Comput. Appl. Power* **1999**, *12*, 22–28.
5. Ilic, M. The information technology (IT) role in future energy generation, distribution, and consumption. In *The Power Engineering Society Winter Meeting IEEE*; IEEE: Piscataway, NJ, USA, 2001; pp. 196–198.
6. *European Turbine Network (ETN) Micro Gas Turbine Technology, ETN Micro Gas Turbine Technology Summary*; ETN: Brussels, Belgium, 2018; Available online: etn.globa (accessed on 15 October 2022).
7. Owens, B.Y.B. The Rise of Distributed Power, General Electric Company. 2014. Available online: legacy-assets.eenews.net (accessed on 15 October 2022).
8. El-Khattam, W.; Salama, M. Distributed generation technologies, definitions, and benefits. *Electr. Power Syst. Res.* **2004**, *71*, 119–128. [CrossRef]
9. Hanssen, J.; Riikonen, A.; Karlsson, G.; Stokholm, R.; Veland, B.J.; Pedersen, A. Operating Experiences from 18 Microturbine Applications for CHP and Industrial Purposes. *Engineering* **2004**, 1–20. Available online: https://www.semanticscholar.org/paper/OPERATING-EXPERIENCES-FROM-18-MICROTURBINE-FOR-CHP-Hanssen-Riikonen/6aa7aaea2f6788359cad78e86c1a436c4a4af880 (accessed on 15 October 2022).
10. Suter, M. Active Filter for a Micro Turbine. In Proceedings of the Twenty-Third International Telecommunications Energy Conference INTELEC, Edinburgh, UK, 18 October 2001; pp. 162–165. [CrossRef]
11. Biomass Combined Heat and Power Catalog of Technologies. 2007. Available online: www.epa.gov/chp (accessed on 15 October 2022).
12. Joh, L.; Del Monaco, P.E. The role of distributed generation in the critical electric power infrastructure. In Proceedings of the IEEE 2001 Winter Power Meeting, Columbus, OH, USA, 28 January–1 February 2001; pp. 144–145.
13. Paepe, W.D.e.; Delattin, F.; Bram, S.; Ruyck, J.D.e. Steam injection experiments in a microturbine—A thermodynamic performance analysis. *Appl. Energy* **2012**, *97*, 569–576. [CrossRef]
14. Ali, A.; Li, W.; Hussain, R.; He, X.; Williams, B.; Memon, A. Overview of Current Microgrid Policies, Incentives and Barriers in the European Union, United States and China. *Sustainability* **2017**, *9*, 1146. [CrossRef]
15. The Official Website of the European Union. 2030 Climate & Energy Framework | Climate Action. Available online: https://ec.europa.eu (accessed on 15 October 2022).
16. *ETN R&D Recommendation Report*; ETN Global: Brussels, Belgium, 2018. Available online: https://etn.global/wp-content/uploads/2018/10/RD-Recommendation-Report-October-2018.pdf (accessed on 15 October 2022).
17. Romankiewicz, J.; Marnay, C.; Zhou, N.; Qu, M. Lessons from international experience for China's microgrid demonstration program. *Energy Policy* **2014**, *67*, 198–208. [CrossRef]
18. Ustun, T.S.; Ozansoy, C.; Zayegh, A. Recent developments in microgrids and example cases around the world–A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4030–4041. [CrossRef]
19. Renewable Energy Agency I; IRENA. Global Renewables Outlook: Energy Transformation 2050, Abu Dhabi United Arab Emirates. 2020. Available online: www.irena.org (accessed on 15 October 2022).
20. US EPA O. Catalog of CHP Technologies. September 2017. Available online: https://www.epa.gov/chp/catalog-chp-technologies (accessed on 15 October 2022).
21. Brauner, G.; D'Haeseleer, W.; Gehrer, W. Electrical Power Vision 2040. In *A Document from The EUREL Task Force*; EUREL: Brussels, Belgium, 2012; Available online: www.eurel.org (accessed on 15 October 2022).
22. Oltra, C.; Upham, P.; Riesch, H. Public Responses to CO_2 Storage Sites: Lessons from Five European Cases. *Energy Environ.* **2012**, *23*, 227–248. [CrossRef]
23. International Energy Agency. Energy Technology Perspectives 2014 Harnessing Electricity's Potential. Available online: http://www.iea.org (accessed on 15 October 2022).
24. European Commission. Joint Research Centre, Brief on Biomass for Energy in the European Union. 2019. Available online: https://data.europa.eu/doi/10.2760/546943 (accessed on 15 October 2022).
25. Lasseter, R.H. MicroGrids. In Proceedings of the 2002 IEEE Power Engineering Society Winter Meeting (Cat. No.02CH37309), New York, NY, USA, 27–31 January 2002; pp. 305–308. [CrossRef]
26. Aslanidou, I.; Rahman, M.; Zaccaria, V.; Kyprianidis, K.G. Micro Gas Turbines in the Future Smart Energy System: Fleet Monitoring, Diagnostics, and System Level Requirements. *Front. Mech. Eng.* **2021**, *7*, 51. [CrossRef]
27. Soshinskaya, M.; Crijns-Graus, W.H.; Guerrero, J.M.; Vasquez, J.C. Microgrids: Experiences, barriers and success factors. *Renew. Sustain. Energy Rev.* **2014**, *40*, 659–672. [CrossRef]
28. Bohn, D. *Micro Gas Turbine and Fuel Cell: A Hybrid Energy Conversion System with High Potential*; von Kármán Institute: Rhode-St-Genèse, Belgium, 2004; NATO Research & Technology Organisation, Report number: RTO-EN-AVT-131.

29. Colson, C.M.; Nehrir, M.H. A review of challenges to real-time power management of microgrids. In Proceedings of the IEEE Power and Energy Society General Meeting, PES '09, Calgary, Canada, 26–30 July 2009. [CrossRef]
30. Bhaskara, S.N.; Chowdhury, B.H. Microgrids—A review of modeling, control, protection, simulation, and future potential. In Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012. [CrossRef]
31. Energy Statistics—An Overview. 2018. Available online: https://ec.europa.eu (accessed on 15 October 2022).
32. Commission Recommendation (EU). 2016/1318 of 29 July 2016 on Guidelines for the Promotion of Nearly Zero-Energy Buildings and Best Practices to Ensure That, by 2020, all New Buildings are Nearly Zero-Energy Buildings, OJ L 208 02.08.2016. p. 46. Available online: http://data.europa.eu/eli/reco/2016/1318/oj (accessed on 15 October 2022).
33. Gros, S.; Jakus, D.; Vasilj, J.; Zanon, M. Day-ahead scheduling and real-time economic MPC of CHP unit in microgrid with smart buildings. *IEEE Trans Smart Grid* **2019**, *10*, 1992–2001. [CrossRef]
34. Kelly, K.A.; McManus, M.C.; Hammond, G.P. An energy and carbon life cycle assessment of industrial CHP (combined heat and power) in the context of a low carbon UK. *Energy* **2014**, *77*, 812–821. [CrossRef]
35. Chilvers, J.; Foxon, T.J.; Galloway, S. Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights, and opportunities. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2017**, *231*, 440–477. [CrossRef]
36. Facchini, A. Distributed energy resources: Planning for the future. *Nat. Energy* **2017**, *2*, 17129. [CrossRef]
37. Björnebo, L.; Spatari, S.; Gurian, P.L. A greenhouse gas abatement framework for investment in district heating. *Appl. Energy* **2018**, *211*, 1095–1105. [CrossRef]
38. Williams, J.H.; DeBenedictis, A.; Ghanadan, R. The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity. *Science* **2012**, *335*, 53–59. [CrossRef]
39. Fais, B.; Sabio, N.; Strachan, N. The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency, and renewable targets. *Appl. Energy* **2016**, *162*, 699–712. [CrossRef]
40. Jägemann, C.; Fürsch, M.; Hagspiel, S.; Nagl, S. Decarbonizing Europe's power sector by 2050—Analyzing the economic implications of alternative decarbonization pathways. *Energy Econ.* **2013**, *40*, 622–636. [CrossRef]
41. Tokimatsu, K.; Yasuoka, R.; Nishio, M. Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use. *Appl. Energy* **2017**, *185*, 1899–1906. [CrossRef]
42. Kaplan, P.O.; Witt, J.W. What is the role of distributed energy resources under scenarios of greenhouse gas reductions? A specific focus on combined heat and power systems in the industrial and commercial sectors. *Appl. Energy* **2019**, *235*, 83–94. [CrossRef] [PubMed]
43. Resource Dynamics Corporation. *Cooling, Heating, and Power for Industry: A Market Assessment*; Resource Dynamics Corporation: Vienna, Austria, 2003.
44. Liu, M.; Shi, Y.; Fang, F. Combined cooling, heating and power systems: A survey. *Renew. Sustain. Energy Rev.* **2014**, *35*, 1–22. [CrossRef]
45. Zampilli, M.; Bidini, G.; Laranci, P.; D'Amico, M.; Bartocci, P.; Fantozzi, F. Biomass Microturbine Based EFGT and IPRP Cycles: Environmental Impact Analysis and Comparison. In Proceedings of the ASME Turbo Expo. Vol. 3. American Society of Mechanical Engineers Digital Collection, Charlotte, NC, USA, 26–30 June 2017. [CrossRef]
46. Nascimento, M.A.R.D.; de, L.; dos Santos, E.C.; Gomes, E.E.B.; Goulart, F.L.; Velsques, E.I.G.; Miranda, R.A. Micro Gas Turbine Engine: A Review. In *Progress in Gas Turbine Performance*; Ernesto, B., Ed.; IntechOpen: London, UK, 2013. [CrossRef]
47. Ismail, M.S.; Moghavvemi, M.; Mahlia, T.M.I. Current utilization of microturbines as a part of a hybrid system in distributed generation technology. *Renew. Sustain. Energy Rev.* **2013**, *21*, 142–152. [CrossRef]
48. Saravanamuttoo, H.; Rogers, C.; Cohen, H.; Straznicky, P. *Gas Turbine Theory*, 6th ed.; Prentice Hall: Hoboken, NJ, USA, 2009.
49. Rodgers, C.; Watts, J.; Thoren, D.; Nichols, K.; Brent, R. *Microturbines. Distributed Generation: The Power Paradigm for the New Millennium*; Borbely, A.M., Kreider, J.F., Eds.; CRC Press: Boca Raton, FL, USA, 2013; pp. 119–150.
50. Lammel, O.; Schmitz, G.; Aigner, M.; Krebs, W. FLOX® Combustion at High Power Density and High Flame. *ASME J. Eng. Gas Turbines Power* **2010**, *132*, 121503. [CrossRef]
51. Lückerath, R.; Meier, W.; Aigner, M. FLOX combustion at high pressure with different fuel compositions. *ASME Turbo Expo 2007 Power Land Sea Air* **2007**, *1*, 1–9. [CrossRef]
52. Reinert, N. Combined Heat and Power-Technology Review and Analysis for a Residential Building. Master's Thesis, University of Tennessee at Chattanooga, Chattanooga, TN, USA, 2012.
53. Goldstein, L.; Hedman, B.; Knowles, D.; Freedman, S.I.; Woods, R.; Schweizer, T. *Gas-Fired Distributed Energy Resource Technology Characterizations*; National Renewable Energy Lab.: Golden, CO, USA, 2003. [CrossRef]
54. Chan, T.F.; Lai, L.L. Permanent-magnet machines for distributed power generation: A review. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–6. [CrossRef]
55. Liss, W.E. Natural Gas Power Systems for The Distributed Generation Market. In Proceedings of the Power-Gen International 99 Conference, Burlingame, CA, USA, 25–28 July 1999.
56. Leal-Arcas, R.; Rios, J.A.; Akondo, N. Energy Decentralization in the European Union. *Georget. Environ. Law Rev.* **2019**. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3333694 (accessed on 15 October 2022).
57. McDonald, C.F. Low-cost compact primary surface recuperator concept for microturbines. *Appl. Therm. Eng.* **2000**, *20*, 471–497. [CrossRef]
58. Pilavachi, P.A. Mini- and micro-gas turbines for combined heat and power. *Appl. Therm. Eng.* **2002**, *22*, 2003–2014. [CrossRef]

59. Kolanowski, B.F. Introduction and History of the Microturbine. In *Guide to Microturbines*; River Publishers: Gistrup, Denmark, 2004; pp. 1–12. Available online: https://ieeexplore.ieee.org/document/9558413 (accessed on 15 October 2022).
60. Next Generation of Micro Gas Turbines for High Efficiency, Low Emissions, and Fuel Flexibility. 2020. Available online: https://cordis.europa.eu/project/id/861079 (accessed on 15 October 2022).
61. Corporation, C.T. Capstone Low Emissions MicroTurbine Technology, White Paper Capstone Corporation, California USA, 6 March 2000. Available online: www.bioturbine.org (accessed on 15 October 2022).
62. Banihabib, R.; Assadi, M. *Dynamic Modelling and Simulation of a 100 kW Micro Gas Turbine Running with Blended Methane/Hydrogen Fuel*; ASME Turbo Expo: Rotterdam, The Netherlands, 2022.
63. Banihabib, R.; Obrist, M.J.; Assadi, M.; Jansohn, P. *Micro Gas Turbine Modelling and Adaptation for Condition Monitoring*; Global Power and Propulsion: Chania, Greece, 2022.
64. Pinelli, M.; Suman, A.; Casari, N.; Reale, F.; Sannino, R. Numerical Modeling of Energy Systems Based on Micro Gas Turbine: A Review. *Energies* **2022**, *15*, 900. [CrossRef]
65. Kanelopoulos, K.; Stamatis, A.; Mathioudakis, K. Incorporating neural networks into gas turbine performance diagnostics. In *ASME 1997 International Gas Turbine and Aeroengine Congress and Exhibition. Volume 4: Manufacturing Materials and Metallurgy*; IGTI Scholar Award: Orlando, FL, USA, 1997. [CrossRef]
66. Volponi, A.J.; Sundstrand, H.; Ganguli, R.; Daguang, C. The Use of Kalman Filter and Neural Network Methodologies in Gas Turbine Performance Diagnostics: A Comparative Study. In *Power for Land, Sea, and Air. Volume 4: Manufacturing Materials and Metallurgy*; Diagnostics and Instrumentation Education: Munich, Germany, 2000. [CrossRef]