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New insights into the potential of the gas microturbine in microgrids and industrial applications

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Highlights

- Provides novel insight into the coupling of gas microturbine with microgrid for decentralised power generation.
- New applications for gas microturbine in microgrids and the industry are described.
- Gas microturbine proves to be an excellent primary source for microgrid operation with various possibilities in an application.

Abstract

This paper gives a comprehensive insight into gas microturbine (GMT) as a part of microgeneration systems. The gas microturbine is a highly effective source that can operate on various types of fuel, including a low-percentage methane fuel such as biogas or landfill gas. The microturbine is widely used in an industrial, rural and commercial application that can benefit from combined heat and power production as a prime or backup source. A microgrid is a modern way to support decentralised power production. It can operate in off-grid mode or as a tool to stabilise the grid and help with peak-shaving as well as to supply remote areas with generated power. The combination of gas microturbine as a prime mover for the microgrid is a smart solution that can quickly react and implement renewable and new technologies. The GMT can be coupled with solar photovoltaics, wind turbine, fuel cells or combustion engines. Use of these technologies can create a sophisticated, stable and highly effective power system. Based on the findings, the combination of microgrid and gas microturbine is very viable and favourable in terms of efficiency, controllability, stability and variety of applications. This paper provides a survey in the field of gas microturbine, its operation, industrial applications, software for microturbine integration, microgrid operation, and coupling the microgrids with gas microturbines, as well as possible challenges and perspectives for this area of combined power generation.

Keywords: gas microturbine, microgrid, industry, application

Abbreviations

Abbreviation	Definition
CAGR	Compound annual growth rate.
CHP	Combined heat and power
CCHP	Combined cool, heat and power
DC	Direct current
DER	Distributed energy resource.
DG	Distributed generation
EMT	Electromagnetic transients
EMTDC	Electromagnetic Transients including DC Software.
GHG	Greenhouse gas

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GMT	Gas microturbine
HOMER	Hybrid Optimization of Multiple Energy Resource software.
LCA	Life cycle assesment
LPG	Liquified petroleum gas
NSGA-II	Non-dominated Sorting Genetic Algorithm 2.
ORC	Organic Rankine cycle
PSCAD	Power System Computer Aided Design.
PV	Photovoltaic cell
RH	Relative humidity
ROO-FIT	Renewals Obligation Order Feed-In Tariff.
SOFC	Solid oxide fuel cells
SPWM	Sinusoidal pulse width modulation.
SW	Software
CO_2	carbon dioxide
NO_x	nitrous oxide related chemicals
SO_2	sulphur dioxide
kg CO_2 eq	kilograms of equivalent carbon dioide emitted
Rpm	rotations per minute
MVA	mega voltamperes, unit for apparent power

1. Introduction

With global resolution focusing on climate change and sustainable development, there is an uprising trend of development efforts on a local scale [1] and even in developing countries [2]. The United Nation General Assembly [3] laid out one of the most challenging sustainable goals to “ensure access to affordable, reliable, sustainable modern energy for all (Goal 7)”. Rao et al. [4] also pointed out that the energy requirement per capita in developing countries such as India, Brazil and South Africa will continuously be increasing with time, giving a perspective that solutions to energy sustainable goals will need to be expandable in terms of capacity [5]. The current situation strongly relates to the development of reliable, renewable-integrated micro energy systems that can be easily deployed in various parts of the world while having flexibility on capacity. On top of this, deployed micro energy systems must also maintain economic feasibility to make implementation sustainable for operators [6]. Such integrated energy systems must be able to bring improvements in terms of social, economic and environmental aspects [7] of the sustainable development project.

For such applications, standalone renewable systems such as wind turbines, solar panels [8], hydropower [9] and other renewable systems have been implemented in various parts of the world. Chauhan and Saini [10] provided an excellent review of the integration of such energy systems with insights on system design and control. Nevertheless, the development in such renewable systems has been slow due to many problems in institutions, market systems, knowledge, and existing infrastructure [11]. A problem from the technical aspect is that renewables usually operate in cycles and have high uncertainties [12]. This leads to many reliability challenges and causes many annual failures within renewable systems [13]. To improve the reliability of systems under uncertainty, Moreira et al. [14] proposed the co-optimization of renewable energy generation and transmission. A Non-dominated Sorting Genetic Algorithm (NSGA-II) was used by Kamjoo et al. [15] to optimize renewable systems under chance constraints. Although various numerical optimization efforts were carried out to obtain optimal investment strategies [16] and energy system planning [17] under uncertainty, real-time predictions of renewable energy generation depend on numerous factors and are impossible to perfectly predict [18]. Thus, the integration of renewable systems with stable sources such as gas microturbine (GMT) as a hybrid is particularly favourable in terms of reliability [19].

Nehrir et al. [20] reviewed that a hybrid of renewable and alternative energy source systems have achieved successes in Norway, Hawaii, Austria, Greece, Japan, United States and other countries around the world. Evidently, hybridizing renewable systems has shown effective practicality in systems design.

Gas Microturbine (GMT) is one of the most versatile and efficient energy technologies that can be integrated with renewable sources in many configurations [21]. The multiple functionalities of GMT allow it to be operated as an islanding source in isolated scenarios, in distributed generation and as a backup generator [22]. This situation gave rise to much interest in research, peaking at a total document count of almost 1000 research documents in academia as of 2019 (see Figure 1(a)). In industry, the global markets for GMT were also growing with a compound annual growth rate (CAGR) of 9.23%, forecasted to reach 364 million USD in 2026 (see Figure 1(b)). With this, we speculate that the GMT market is heading towards a more sustainable power generation with highly-integrated systems [23], distributed multi-energy generation which includes cooling [24], and smaller but high energy efficiency designs [25]. With high potential for energy cost savings [26] and lowering capital costs of investment, it is expected that more industrial factories will utilize GMTs locally due to its flexibility on sustainable, maintainable and reliable energy generation [27]. Throughout the years, GMT has received many technological improvements. Early GMT technologies had total combined heat and power (CHP) efficiency lower than 50% [28], which was well lower than that of a typical cogeneration system. Nevertheless, the potential of GMT with potentially no lubrication and high energy efficiency were attracting more interest in the technology. In this period, researchers had put efforts into combining GMT and fuel cells or fired boilers to attain better efficiencies [29]. With more global interests in promoting CHP technologies in early 2000, the total CHP efficiency of pioneering GMT technologies was reported up to 61-68% [30]. At this point, Pilavachi [31] had already predicted that future GMT systems would easily achieve total CHP efficiencies up to 80% based on theoretical thermodynamics. Later, much more incremental improvement was made to the GMT technology, which includes component design such as turbomachinery, rotor configuration, combustor, recuperator, control and other aspects [32]. In this period, the quality of GMT from Capstone Turbine Corporation became widely recognized, and many researchers were doing improvement works based on the Capstone design [33]. The possibility of using alternative fuels for GMT was also studied by Krishna [34]. Further maturing of the technology led to a possibility of ultra-high rotational speed for GMT [35]. Dessornes et al. [36] reported that total efficiency of 93% was achieved at 70,000 rpm with careful design of gas bearing and suitable testing conditions. Nevertheless, the nominal total CHP efficiency of commercial GMT ranges between 80 to 90% currently, which greatly exceeds that of conventional cogeneration systems (typically 65%).

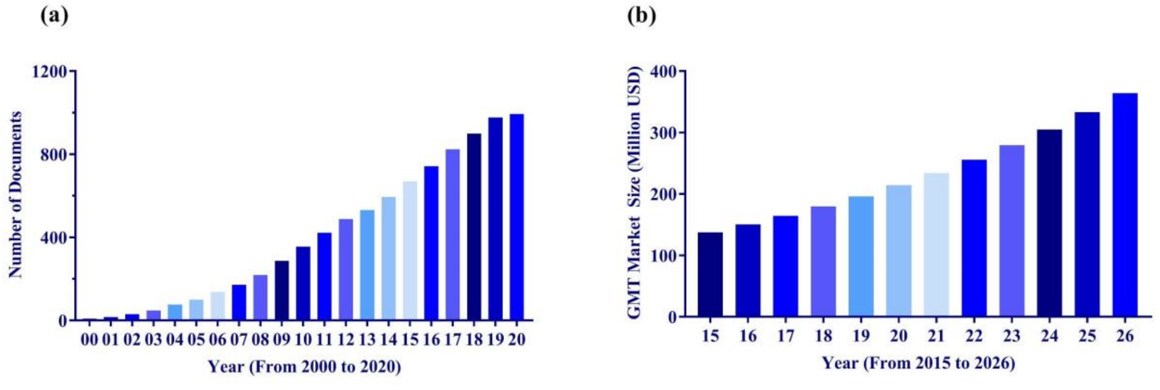


Figure 1: Trends of (a) total research documents from 2000 to 2019 (source: SCOPUS database) (b) forecasted global GMT market size from 2015 to 2026 [37]

Various researchers also studied and reviewed the possibility of integrating a hybrid renewable-GMT system into distributed energy generation due to its capability to easily reach over 80% total energy efficiency [22]. GMT can also simultaneously generate heat and power, making it a very viable technology for CHP applications at low capacity and high efficiency [25]. An additional advantage of using GMT is that there is flexibility for its fuel, which includes natural gas, biogas, waste gas, flare gas, liquified petroleum gas and other fuels [38]. Therefore, the renewable mix of the power generated can be easily controlled by the operator. Streimikiene and Baležentis [39] carried out a multi-criteria analysis of micro-CHP technologies and found GMT to be the best technology (compared to reciprocating engines, Stirling engines and fuel cells) in terms of efficiency, costs, environmental considerations and reliability. Medrano [40] demonstrated that integration of GMT for the energy demand of medium capacity could result in 4.3 to 7 years of the payback period. Despite the technological advantages of GMT, there are economic challenges for GMT in the past few years due to reciprocating engines being significantly cheaper [31]. Barin et al. [41] also expressed that the cost for GMT is less attractive than photovoltaic and wind turbines. The main cause of the expensive price for GMT is due to fractionated proprietary ownership of the design [42]. However, it is expected that high costs of GMT will significantly decrease in the upcoming years due to many key GMT patents reaching expiration ([43–45]) constraints.

Apart from decreasing investment costs, global policies in various countries are also supporting micro-generation of heat and power in the form of feed-in tariffs [46] and various subsidies [47]. Within a micro-CHP plant, Kaikko and Backman [26] carried out the techno-economic analysis for GMT concluding that fuel and electric prices were crucial for the implementation. The work also highlights the economical flexibility of GMT-based micro-CHP to profit from heat and power with a well-designed heat recuperator. Campanari and Macchi [48] showed that GMT systems could also benefit the most from a lowered fuel price and elevated electricity tariff within a combined cooling, heating and power (CCHP) plant. Nevertheless, with a case study in Iran, Mosadeghi et al. [49] demonstrated that investment effort does not change much for GMT during subsidies removal when compared with full renewable systems such as photovoltaic and wind turbines. With policies in various countries such as Europe, United Kingdom [50], United States [51], China [52], Malaysia [53] and other countries providing incentives to CHP and renewables, GMT-based system sees a healthy future for implementation in the next few years. A detailed compilation of policies, schemes and acts that favour integration of GMT systems in various countries are compiled in Table 1.The general trends of policies are providing a bigger incentive for smaller power generation capacity and heavily rewarding renewable fuels. Therefore, micro-energy systems such as GMT can either integrate with renewable systems or directly utilise renewable fuels to maximize leverages from these schemes. Meanwhile, heat generation incentives highly depend on the nation of implementation and depend on case-to-case. For energy generation, energy storage and backup generation provides more reliable and robust operation [54] which improves the certainty to meet criteria in legal schemes and policy. Alternatively for energy users, energy storage and back-up generation for peak-shaving [55] can lower costs for maximum demand penalties [56]. For green initiative in CHP systems, it is common to have a regenerative mode design that can improve up to 22.5 % in electrical efficiency [57]. Other industrial efforts include integrating hydropower, wind turbines, solar power [58], biomass [59], biogas [60] and other renewables within CHP systems.

Table 1: Policies, schemes and acts favouring the integration of renewables and GMT (Source: Compiled from RES LEGAL Europe Database)

Country	Schemes/ Acts	Related details
Austria	Feed-in Tariff Ökostromgesetz (ÖSG) 2012, Environmental Aid Act	Feed-in tariff of 10.10 – 21.78 €cents per kWh for biogas feed depending on maximum bottleneck capacity. Investment subsidies are also provided for heating from renewables.
Belgium	Quota System and Net-	Specific details of support are divided into three regions

	metering	(Brussels, Flanders and Wallonia). Electricity producers are required to submit certificates to prove that an increasing proportion of the electricity supplied is from renewables. Heat subsidies are also available for CHP with biogas and biomass as renewable feedstock.
Bosnia and Herzegovina	Electricity Law and Renewable Energy Sources Law	After obtaining status as a “privileged power producer”, feed-in tariffs are obtained with guaranteed price depending on power capacity.
Bulgaria	Energy and Water Regulatory Commission	Renewable energy installations with capacity below 4 MW can enjoy feed-in tariff. The tariff is determined annually by the commission.
Croatia	Act on Renewable Energy Sources and High-efficiency Cogeneration	Guaranteed purchase price for renewable power with lesser than 500 kW capacity. Public tenders are held annually to obtain this tariff.
Czech Republic	Act on promoted Energy Sources	Renewable power generation with a capacity of less than 100 kW can enjoy feed-in tariff. Payment of the feed-in tariffs are managed by the Ministry of Industry and Trade. Companies are also subsidized (approximately from €9,600 to 3.8 million depending on size of company and renewable source) for the construction of cogeneration plants from biomass and solar energy.
Finland	Act on Production Subsidy for Electricity Produced from Renewable Energy Sources	Premium tariff is available for power from biogas with a capacity of less than 19 MVA. The premium tariff is equal to € 83.5 per MWh subtracted by the average market price of the previous three months. “Heat bonus” are given to efficient biomass (€ 20 per MWh) and biogas (€ 50 per MWh) CHP plants.
France	Act on Energy Transition for Green Growth	Feed-in tariff support for solar power generation with capacity less than 100 kW and biogas power generation with capacity less than 500 kW (17.5 €ct per kWh) . Biomass plants with heat production over 1,000 toe per year can be also subsidized under heat fund.
Germany	Renewable Energy Sources Act (EEG 2017)	Power generation from biomass and biogas below 100 kW can enjoy feed-in tariffs. Manure-based biogas are limited to a capacity of below 75 kW. The monetary amount of feed-in tariffs depends on many factors. For renewable district heat grids, up to € 600,000 (with a maximum of 60% of eligible costs) can be supported.
Netherland	Electricity Act, Renewable Energy Production Incentive Scheme	Net-metering is available to all types of renewable energy with grid connection throughput value smaller than 3*80A. Premium tariff is provided by the Dutch government for biogas (including gasification and fermentation) and biomass

		CHP. The amount of feed-in tariff depends on installation size and phase of the scheme.
Norway	Electricity Certificates Act	The Quota system is implemented in Norway to mandate producers and consumers of electricity to use a certain quota of renewables within the energy mix. The system uses a certificate trading system.
Sweden	Electricity Certificates Act, Energy Tax Act	Sweden also uses a similar Quota system as Norway. On top of that, subsidy is granted for up to 30% the eligible costs for solar installations. Electricity generated in a plant with lower than 50kW capacity is not taxable, where this value is higher for renewables. Heat energy from renewables is also exempted from energy, Nitrous oxide and carbon taxes.
Switzerland	Energy Act, Energy Promotion Regulation	All renewable energy generators can enjoy feed-in tariff up to 25 years. For biomass generated power, the highest tariffs are for the performance category below 50 kW.
United Kingdom	The Feed-in Tariffs Order, The Electricity Act, The Energy Act	Microgeneration certification scheme is provided to power generators up to 50 kW with a microCHP. Power generation up to 5 MW can also enjoy tariffs from Renewals Obligation Order Feed-In Tariff (ROO-FIT) scheme. Moreover, renewable electricity is exempted from taxes by the Carbon Price Floor mechanism. Both domestic and non-domestic renewable heat generation enjoy an incentive with a fixed amount (up to 23.36 €ct per kWth) for 20 years.

At this point, the potential of GMT is evident due to its technological flexibility while maintaining high efficiency. Moreover, the economic potential for GMT is expected to improve on account of the expiration of key GMT patents and global efforts in CHP and renewables incentives. The subsequent section of this paper will guide energy consumers and operators to integrate GMT into both industrial systems and local microgrid systems to promote higher energy efficiency, waste energy utilisation, improvement of renewable mixes and system stability. This work is based on thorough research of up-to-date scientific literature; however, only very relevant papers were chosen. Therefore, this paperwill concisely cover a GMT integration perspective from system design, control and operation with coverage software, challenges and future directions for GMT-based systems.

2. Gas Microturbine

Gas microturbine is a technology that can provide a highly effective source of energy. The technology of the GMT was developed in the 1950s; however, it is still considered a modern and efficient system. The power output of the GMT is classified to a range of 30-350 kW, it can be increased by parallel connection of a number of the GMT units. Such systems can reach the power output up to tens of MWs. The overall efficiency is about 80-90% with an electrical efficiency of about 30%. The GMT can be sorted by several shafts design – single-shaft or double-shaft. With double-shaft configuration, more moving additional parts that can cause more demands on maintenance or even malfunction.

The Brayton cycle with isobaric fuel combustion is the main working principle of the GMT. The mixture of ambient air and fuel is combusted, flue gases expand through the turbine that powers the generator. Additional heat is used for preheating the inlet air before compression and mixing with the fuel. As the primary fuel is considered the natural gas, biogas, landfill gas and propane gas etc. In case of the biogas and landfill gas, the GMT can be determined as a green or renewable source of energy. Also, the GMT can process fuel with lower quality composition of impurities [61]; therefore, the GMT is adaptable for various uses.

Another advantage of GMT is compact size and low weight given to the power output, low maintenance demands, low noise and vibration [62]. Nevertheless, the biggest asset of the GMT is high-temperature flue gases (around 275 °C) with high purity and low NO_x emission that easily meets the emission limits. With these flue gases that can be further utilised in the process, the GMT can be used as a high-efficiency source for CHP or even CCHP.

On the other side, the power output of GMT is sensitive to ambient conditions, especially temperature and pressure (see Chapter 4). The obstacle for broader use of GMT in industry and commercial sectors is the higher investment cost, about 1,300-1,800 USD/kW [63]. These are caused by a patent for crucial parts of the GMT units held by the GMT market leader, Capstone Turbine Corporation. In upcoming years it is expected the patent protection will end up and therefore the price of the units will slowly decrease. Also, with the increasing number of GMT applications, the costs reduce [64].

The GMT is mostly used as a backup source, for island or offshore applications, or as a part of complex power generation systems. It can be said the GMT is suitable for industry and commercial use because of the variability of the primary fuel, usable flue gases, capacity, stability of power production and low maintenance requirements as it is confirmed by do Nascimento et al. [65].

2.1 Integration of GMT in industry

As it was mentioned in section 2, the GMT is a suitable energy source for industrial applications. However, its expansion is mostly hindered with the price of the unit. The previous review of the authors [66] showed that the GMT is mostly used as a part of sophisticated systems focused more on electrical power generation. The GMT is combined with other highly-effective technologies to increase the overall power output. Often, the GMT flue gases are used to drive, for example, the fuel cells [67] or organic Rankine cycle (ORC) [68]. In the case of CHP application, the GMT is coupled with a heat exchanger for utilisation of the hot flue gases. The heat is used back in the process, preheating the process streams. Only a few applications of flue gas direct use were discovered in published papers. Because of the high heat potential of the flue gas, authors find this fact as a topic of interest for further research.

The CCHP operations are realized by adding the absorption chiller to the system to produce the cold. These applications are mostly used in the food retail industry or for space cooling. Also, specific applications of the additional cold are used for improving the power efficiency by cooling the inlet air.

However, GMT is often used for power generation in wastewater treatment plants, oil and gas facilities, biogas plants and landfill facilities. These areas provide gaseous fuel for the microturbine and further utilise the produced electricity and heat of the flue gas. Because of the progressive technology GMT can operate on biogas, flare gas or landfill gas with a lower percentage of methane, as low as 30% with minimal pretreatment [69]. Operations can benefit from low-cost energy and its direct use in the facility.

According to the leading manufacturer of GMT [38], the use of the unit in wastewater treatment plants, landfill plants or biogas plants is economically viable and environmentally friendly (see Figure 2). Several successful operations in north Italy [70] use the biogas from the digester to run the GMT. The produced electricity is used on the plant and heat from the flue gas is recovered and used to keep the optimal temperature of the digesters or used for heating of the nearby buildings and greenhouses (See Fig. 2). The GMT reaches better efficiency of biogas utilisation than regular gaseous boilers or piston-driven combustion engines. Also, with great combustion technology, the GMT easily meets the strict emission limits of the region without any further treatment [38].

The GMT in a case study by Rasul et al. [71] is used for smaller household area, uses the biogas produced in an anaerobic digester with solar collectors. For better feasibility, the authors recommend using such a system for small agriculture areas where the viability will be better even with a small number of farms that can easily produce enough feed for the digesters.

Wastewater from cassava production, also known as *manipueira*, contains acid but still has potential for biogas production [72]. Before the biogas combustion in the GMT is pretreatment to remove hydrogen sulfide. This solution is environmentally friendly because it eliminates the *manipueira* sludge being dumped and provides low-cost electricity and heat with an amortization period of only 1.3 years.

The landfill area also gives the big potential for GMT applications. According to Kashyap et al. [73], India produces 210 million tonnes of municipal solid waste with 50% organic components. Landfills are mostly open and produced landfill gas is not utilised in any way; only produce methane gas that increases the greenhouse effect and is harmful to our environment. The landfill gas can contain up to 50% of methane gas and the same amount of CO_2 gas [74]. Even with a low methane percentage (less than 30%), the landfill gas can be effectively utilised in GMT as is proposed in this paper. That way, the flaring of the gas is reduced, and electricity and heat are produced [75].

Another study [76] focusing on landfill gas run GMT with 1.16 GJ of recovered heat used for a greenhouse, more heat is used for the hot water heating system. Electricity is used on site of the greenhouse, and the excess is exported to the grid. Authors point out the future task for this system – optimization according to harvesting schedule, crop stage, weather, etc.

Another comprehensive agriculture system using landfill gas to run GMT was studied by Janes et al. [77]. The recovered waste heat is used for nearby greenhouses in winter, and in summer month it is used to desalinate water. The agriculture effluent is used as a fertilizer for the hydroponic crops, the excess CO_2 from the landfill is used to improve the growth of the plants. This system uses fully the sources with great efficiency (about 75%), displacing fossil fuels, lowering the produced emissions of greenhouse gases and decreasing waste production.

Bujak [78] proposed using the syngas generated by thermal treatment of medical waste as a primary fuel for the GMT. The larger hospitality facility with waste production of 220 kg/h reached an efficiency of 79%. However, GMT does not meet the requirements for electricity consumption, although the whole system is economically convenient with payback time only three years.

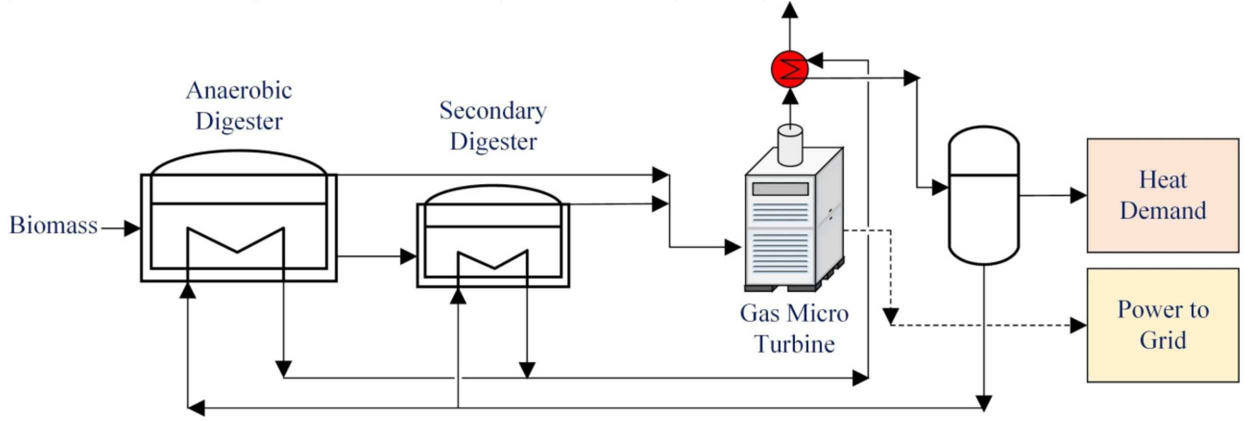


Figure 2: Example of integration of GMT to the biogas plant, wastewater treatment plants or landfill plants

In case of additional thermal energy from the GMT operation, evaporation units can be added to consume the energy. Distillation or evaporation units can be used for desalination, thickening process liquids or produce powder substances as they can be seen in Figure 3. Desalination units are used in combination with GMT in the work of Sanchez et al. [79] who propose a complex system of solarized GMT for electricity and water production. The electricity from the GMT is used to power the reverse osmosis unit and the recovered heat is used for desalination in the multi-effect distillation unit. The results showed that the price of the water is increased with the desalination technology, which is understandable because of the investment for the distillation unit. However, this study shows that the recovered heat from GMT can be effectively applied for other heat demanding processes. The previous part of this paper discussed the advantages of biogas operated GMT in biogas or wastewater treatment plants. Vondra et al. [80] presented the possibility to thicken digestate in evaporation units. There is a great opportunity for GMT to transform the biogas to electricity and heat source for the evaporation unit to reduce the amount of liquid in digestate produced by the plant.

Progressive method is introduced by Holton et al. [81]. Their paper introduces technology to vaporize liquid ethanol and blend with natural gas to create combustion mixture that could replace natural gas in combustion devices. This technology does not need any changes to the regular combustion devices and provides clean burning. The technology was successfully tested on 30 kW GMT including the waste heat recovery for the vaporization of the ethanol.

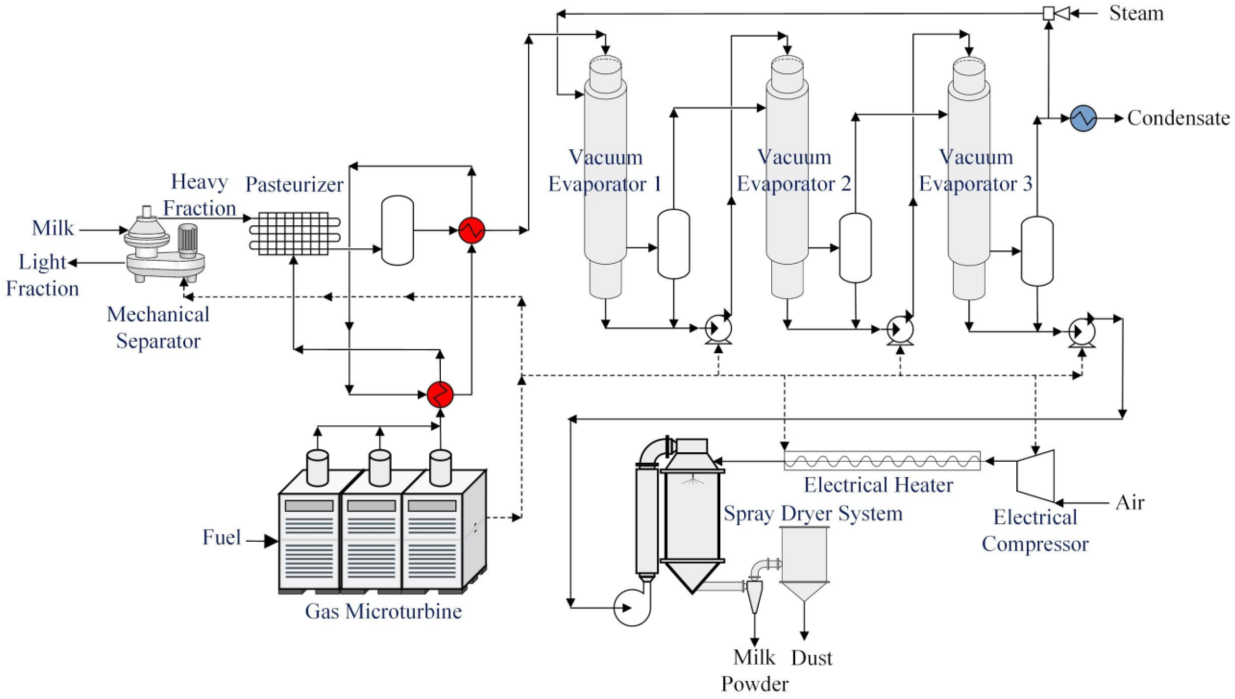


Figure 3: Example of GMT integration to the milk powder production process

Because of clean flue gases with almost zero-emission, it is possible to consider them for direct heating. Máša et al. [82] presented the possibility of laundry drying using the flue gas directly from GMT. The electricity produced by GMT is utilised within the laundry process to run the washing machines, dryers and ironers as well as other devices. The hot flue gas is fed to the dryer and heat exchanger to prepare hot water for the washing. This application of GMT also provides space for advanced optimization of such systems as shown in Figure 4.

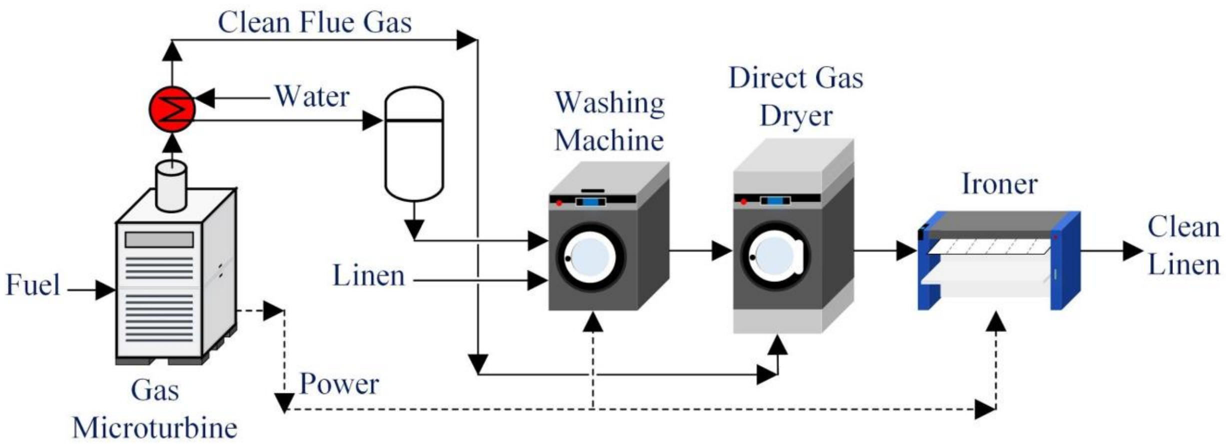


Figure 4: Integration of GMT to the laundry process

The use of GMT is also favourable for oil and gas production sites. The GMT can be used onshore and offshore depending on the specific needs. The GMT is used to combust the flare gas often without any utilisation even though flared gas has an enormous amount of energy that can be used in a more efficient way (see Figure 5). Gas flaring is a commonly used approach to meet technical, regulatory or economic requirements. In 2019, 140 billion cubic metres of gas was flared, producing around 270 megatonnes of CO_2 [83]. However, GMT does not have to be used only for gas flaring.

In Bolivia, the GMT replaced traditional generators as a primary source for natural gas pumping stations. The microturbine uses raw natural gas to power 20 compressors and covers the electricity demand of the station. The GMT proved to be a better and cheaper solution for the natural gas pipeline with significant greenhouse gas reduction [38]. For the offshore application, the GMT uses wellhead gas that would be flared without any use. With the microturbine, the gas is fully utilised and converted into useful energy in the form of electricity and heat. In offshore applications, the GMT units can be doubled and employed as a primary and backup source. [38]

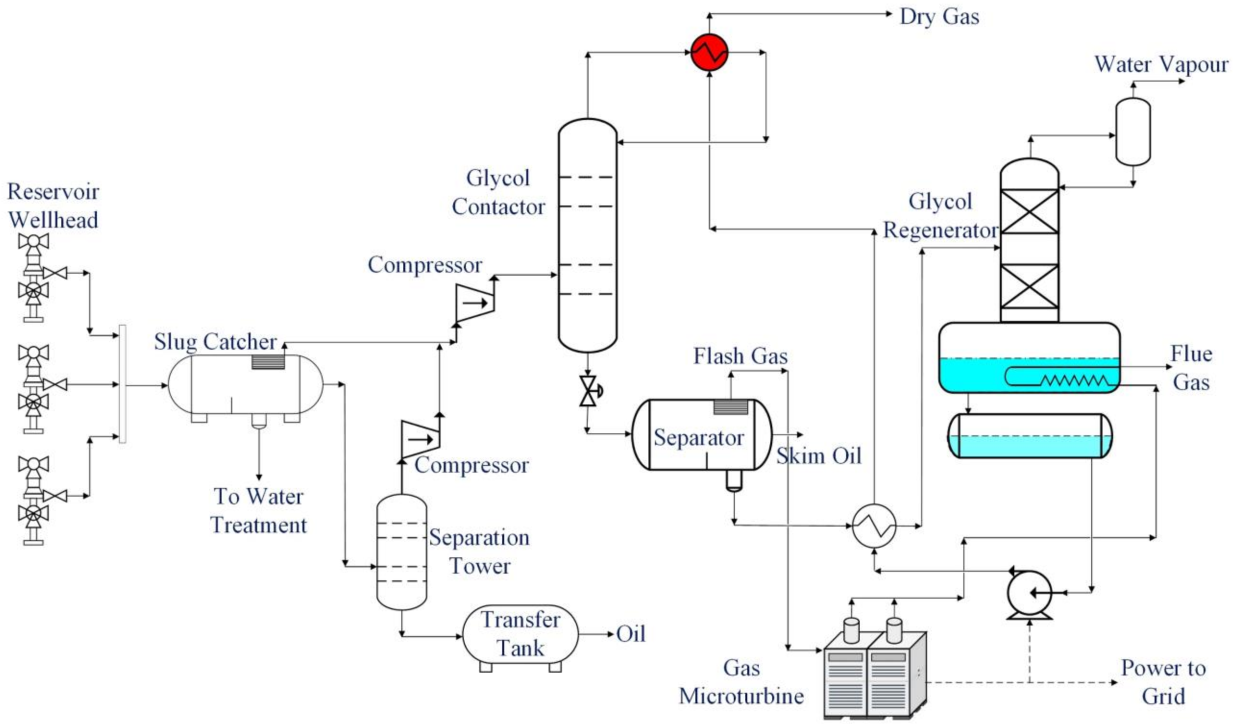


Figure 5: Gas flaring using GMT integrated to the oil and gas production process

With the integration of the GMT to the industrial processes, a rigorous technical-economic analysis has to be made to evaluate the pros and cons of the GMT purchase. Based on the previous review by authors [66] in the design of the integration, the focus has to be mainly on the following factors:

- cost ratio of natural gas and generated electricity,
- purchase prices of heat, electricity and fuel,
- operating time,
- utilising of the flue gases,
- available subsidies.

The importance of positive cost ration of natural gas and electricity from the grid highlights the majority of studied papers. For CCHP application in a sewage treatment plant, Bruno et al. [61] point out that with good cost ratio the payback time decreases and it is even possible to consider more than one GMT unit to cover all electrical demands of the process. Additionally, it opens up more possibilities for utilisation of hot flue gas, such as air conditioning, inlet air cooling, biogas dehumidification, digester heating or hot water preparation [61]. This statement is also confirmed for application for the food retail industry [64]. In this type of industry, it is important to consider climate profile and right utilisation of heat, to prevent significant excess heat and cold energy [84]. The same situation is for the purchase prices of heat, electricity and the fuel for GMT. With a favourable ratio, it is possible to reach a short payback time.

Another factor is the operating time that was mentioned in the CHP application for a coffee roasting facility [85]. For this case, the GMT is rentable with operating time higher than 12 hours per day; otherwise, the investment is too high for most of the facilities. This is supported by Caresana et al. [86] that discusses the fuel consumption and power load of the GMT, which is linear. For these conditions, it is reasonable to keep the GMT fully utilised and make the payback time as short as possible.

With conscientious incorporation of the GMT to the process, it is possible to substitute electrical heating systems such in manufacturing facilities examined by [63]. Thanks to proper integration, the electrical consumption was reduced by 17%, and additional heat sources were reduced.

For a suitable selection of energy source, it is necessary to include available subsidies to the technical-economic analysis, especially for GMT because of the higher investment cost. The subsidy conditions vary for different regions and types of sources. Caresa et al. [86] analyzed the incentives for energy sources for Italy. The system is set to endorse sources with higher electrical efficiency; therefore, the GMT is an unfavourable option. The subsidies should consider the utilisation of waste heat from the flue gases and the overall efficiency of the unit.

With all of these points, the GMT can be very effectively integrated into the industrial processes with all the benefits of high-efficiency combined energy sources.

2.2 GMT and microgrid

Microgrids are locally interconnected loads, devices, energy generators and storage which act as a single controllable entity in relative to the grid [87]. Particularly, with the growing interest in integrating intermittent renewable energy generators into the global energy mix, microgrids show high potential to maintain reliable operation and control [88] in a sustainable manner. The use of the GMT within the microgrid is a well-known approach to the effective system with a gas-based prime mover, although it is still not very common. Real-life operations are being tested and evaluated; these runs can help push the technology forward, as Basu et al. [89] confirmed.

Romankiewicz et al. [90] studied the Sendai microgrid in Japan that uses natural gas units, fuel cells and solar PV to run an island operation mainly for a local hospital, the excess amount of energy is used for other local facilities. CO_2 emissions of the system decreased by 12%, and energy cost reduction was between 14-30%. Authors highlighted the importance of Japanese fundings to build and successfully run such a system. The optimization task of microgrids is further explored in the case study in Chile by Bustos and Watts [91]. A complex microgrid with a diesel generator, the GMT, wind turbine, solar PV and batteries, was created for the isolated village. The optimization was done for an estimated load of the village that was not accurate because of the lack of data, then the sum of fuels and the cost of not supplied energy was minimized. After a successful run of the system, it is estimated that the microgrid needs to be connected to the macro grid or grid in general because of increasing electricity consumption of the community.

Zachar and Daoutidis [92] discussed the suitability of the GMT as a prime source in a microgrid for commercial buildings such as office buildings, hospital, school, retail stores with waste heat recovery systems for space heating. These types of building vary in load shapes (in day or week and also in season) and can be used as a testing facility for a microgrid with the GMT. Authors agreed that space heating loads are not effective for electric load and should be based on gas technologies such a GMT. In a more recent paper of the authors [93] examine the scheduling of the GMT operation. The strict scheduling plan is followed in the case study and prevents the on-off cycling of the GMT and also the violation costs. Moreover, the cost of GMT utilization is only from fuel consumption. In the case of favourable tariff for gaseous fuel, the GMT is a good solution for a highly effective primary source of the microgrid.

Based on studied papers the microgrid using different CHP technologies and renewable resources are environmentally friendly and not as expensive for various end-users in observed locations, as it was confirmed by Zhang et al. [94] who studied the use of natural gas in DER systems. The microgrid with the GMT is successfully tested, especially in commercial and isolated operations. The next step is to use these systems in industrial areas where the utilization can be beneficial for decentralized energy production.

2.3 Software for GMT integration

There is very good software support for integrating GMT into the utility systems and microgrids. This has been also reflected in recent publications where various software systems find application both in the design of systems and in their operational optimization. The two most widely used commercial software (SW) are PSCAD / EMTDC [95] and HOMER Pro [96]. Both SWs are object-oriented and offer a rich database of components that the user connects and configures as needed. The key to choosing one or the other SW is the purpose of the simulation.

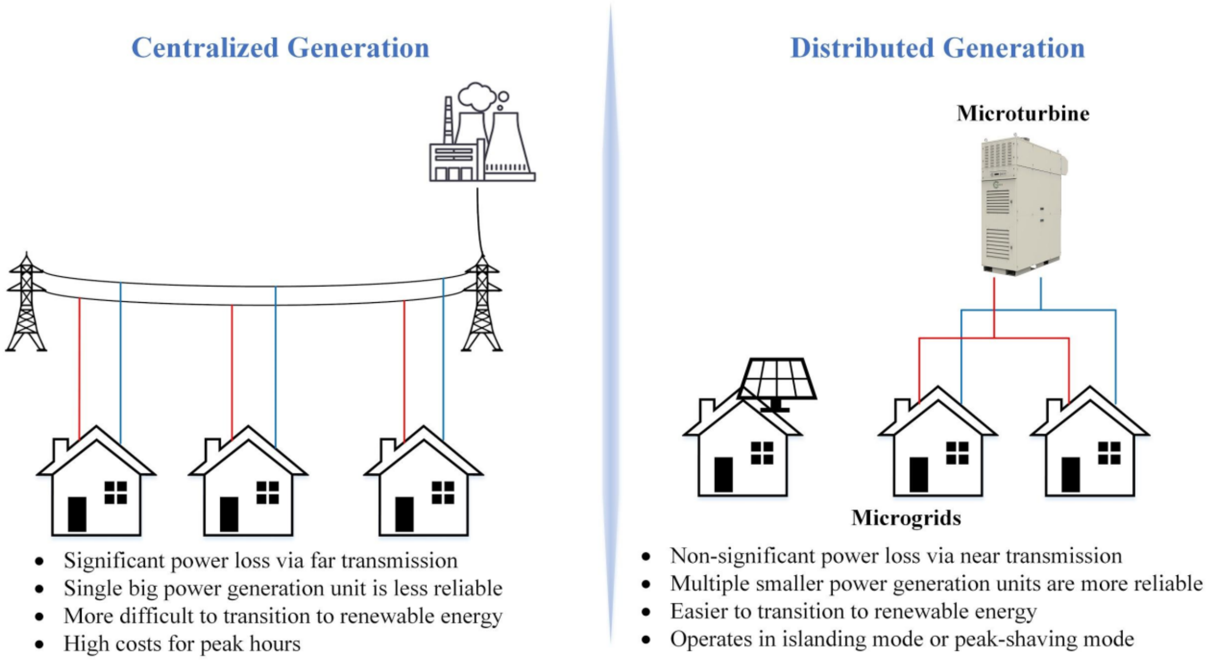
PSCAD / EMTDC is universal SW for power system electromagnetic transient simulations. This software is typically used for detailed dynamic modelling of the power system and allows analysis of the time domain instantaneous responses (also known as electromagnetic transients) connected with switching or various faults. EMTDC (which stands for Electromagnetic Transients including DC) represents and solves differential equations for both electromagnetic and electromechanical systems in the time domain. PSCAD (stands for power system computer-aided design) is then a graphical user interface for EMTDC allowing the user to graphically assemble the circuit, run the simulation, analyze the results, and manage the data in a completely integrated graphical environment [97]. One of the first EMT models with GMT was built for the generation system with a dynamic load [98]. Authors analyze the interactions among the GMT, power electronic converter and the load. Later PSCAD / EMTDC was used for optimal sizing of a battery energy storage system [99] and to design coordinated GMT and battery control strategy [100]. Increased use of renewable energy sources was an important milestone in the use of this software [101]. Microgrid fault protection has become one of the key research topics [102]. Larger models that include, in addition to GMT, other models such as solar photovoltaic (PV) a wind turbine [103] or solid oxide fuel cell (SOFC) [104] were created. These large-scale mixed source models were used for the analysis of complicated failures such as a cascading collapse problem caused by fast-acting distributed energy resources [105]. Of course, PSCAD / EMTDC is widely used beyond GMT integration, especially for dynamic modeling of AC or DC components in electrical engineering [106].

If a broader perspective of the microgrid operation is the aim of the study dealing with system efficiency and economics, authors tend to HOMER Pro software [107]. HOMER is an acronym for Hybrid Optimization of Multiple Energy Resources and the software is focused on techno-economic optimization to find the lowest cost power system that meets all technical requirements from many different possibilities [108]. The software is popularly used by various researchers, especially for renewable microgrid systems analysis. Optimal sizing and management of renewable resources and a storage unit [109] or a solar PV microgrid analysis in the grid-connected and islanded operation [110] are two representative examples.

PSCAD / EMTDC software thus helps with detailed system simulation to develop fault protection and control strategies. HOMER Pro software is suitable for a better understanding of the performance of power systems and techno-economic evaluation of projects. The benefits of software support are growing with the complexity of the microgrid. An alternative to specialized commercial software can be a high-level Matlab/Simulink software with its Simscape Power Systems [111]. The advantages of Matlab software are evident in the synthesis of more complex control algorithms [112] and when a direct connection with the physical model or a real system is available [113].

3. Aspects of GMT-based microgrids

. The microgrid is one of the most promising technologies for distributed generation (DG) of energy [114]. As opposed to traditional centralized, DG saves much more investment costs in transmission and distribution networks. For centralized generation, Allan et al. [115] estimate that the true capital costs can be over $4500/kW while DG enjoys almost no capital costs associated with transmission. Peter and Lehmann [116] also pointed out that power losses during line transmission can also go up to 7%, which greatly damages the economics for centralized generation technologies. Meanwhile with the development of energy efficiency, micro-devices for DG now have comparable total energy efficiency when compared to district power generation. Today, the total energy efficiency for local CHP conversion is over 90% [117] while that of district CHP is only about 60%. Moreover, the implementation of DG has allowed for more diversity of energy sources within the grid, including various renewable energy sources [118]. Zachar et al. [119] estimated that the implementation of microgrids can effectively reduce carbon emission by 5 to 15% when compared to centralized generation by conventional natural gas and coal. As smaller stakeholders are in-charged to implement renewable sources within the microgrid, the decision is much faster than centralized generation technologies which normally requires politics, policy changes and layers of organisational commitments. Microgrids also serves as a stabilizer for the energy market prices, avoiding high-priced energy from centralized grids with distributed energy sources [120]. Some comparison between centralized generation and DG can be found in Figure 6. It is also worth mentioning there are conventionally two modes that microgrids operate at, being islanding mode and peak-shaving mode [121]. The islanding mode functions to disconnect the local grid from the central grid by supplying all energy requirements locally [122]. Alternatively, microgrids running peak-shaving mode respond actively to the centralized grid, supplying energy only when the costs are high or energy supply is in peak timing [123].



- Significant power loss via far transmission
- Single big power generation unit is less reliable
- More difficult to transition to renewable energy
- High costs for peak hours

- Non-significant power loss via near transmission
- Multiple smaller power generation units are more reliable
- Easier to transition to renewable energy
- Operates in islanding mode or peak-shaving mode

Figure 6: Brief comparison between centralized generation and distributed generation.

In a microgrid, the energy source unit commonly consists of PV cells, wind turbine, fuel cells, diesel engine and GMT [124]. The recent design in microgrid combines an unreliable renewable source with a reliable source, for example, PV cells and GMT [125]. Works from Vachirasricirikul et al. [126] also studied the effects of stabilizing the microgrid system and improving reliability by incorporating GMT. This enables a higher ratio of renewables into the energy mix while maintaining the reliability of the system. In this aspect, GMT is a particularly suitable unit to act as a redundancy energy source. The advantage of GMT is that it has a compact size and high energy efficiency due to operation at a higher rotational speed. Moreover, GMT also uses lesser moving parts which lead to lesser maintenance, produces lower noise with short delivery time [127]. Nascimento et al. [65] also reviewed that GMT demonstrates reliable operation which can last up to 25,000 hours with variable speed between 30,000 to 120,000 rpm. More advanced GMT can also provide remote monitoring, no lubrication, uncontaminated exhaust heat and operates with the gas feed of natural gas, associated gas, liquefied petroleum gas (LPG), propane, flare gas, landfill gas, digester gas, diesel, aviation fuel and kerosene [38].

Within the research fields of GMT integration, Rachtan and Malinowski [128] studied the recovery of heat energy from the GMT to act as a CHP. In this aspect, Kaikko and Backman [26] carried out a techno-economic analysis and showed heat recovery using large recuperators are critical for the overall economy of the operation. The approach of using water and steam injection to recover heat energy from a recuperated cycle microturbine was also studied by Lee et al. [129]. It was found that injecting steam at the recuperator inlet can elevate the efficiency of power generation however gives a necessity of anti-corrosion measure. A novel Swiss-Roll recuperator was also proposed by Tsai and Wang [130] to increase heat recovery efficiency by 57.2% and power output per fuel consumption rate by 57.4%. Integration of GMT and organic Rankine cycles (ORC) were also studied by Mago and Luck [131] to further extract more electrical energy from the waste heat of GMT systems. This direction has shown much more possibility in improving the geometry of the radial microturbine impeller within the ORC-integrated system [132].

With demands for cool energy, other researchers such as Seyfouri and Ameri [133] had studied the integration of GMT with absorption refrigeration systems. For this heat-power-cooling trigeneration system, Basrawi et al. [134] analyzed the effects of operation strategy on economics and environmental performance. The work concluded that the system can only generate positive net present value at the end of 25-year lifetime assuming unsubsidized electricity. For higher requirements of cool energy, Huicochea et al. [135] studied the possibility of utilising a double effect absorption chiller with GMT. Further technology development is required to improve the situation in this system and the current scheme of utilising GMT is shown in Figure 7. One of the most promising efforts is to use a solarized GMT (also known as solar-assisted GMT) to improve the thermodynamics and efficiency of the system [136] These solarized GMT can then be implemented within the previously mentioned trigeneration system to give elevated economics and environmental impacts to the project [137]. The work reported a levelled electricity cost of 5.75 US cents/kWh with 114,000 tonnes reduction of annual carbon emission. Other efforts to improve the trigeneration system include using solid oxide fuel cells, biomass combustor, and solar systems also function to improve the GMT-based trigeneration system [138].

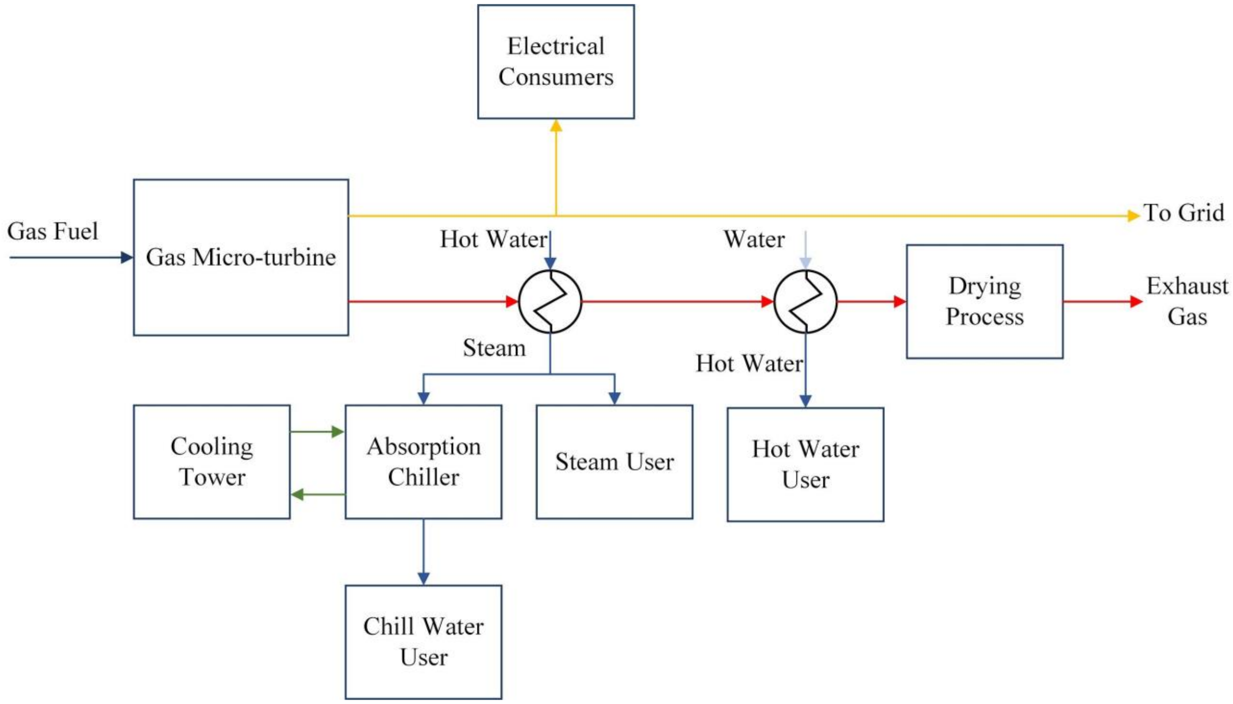


Figure 7: Process scheme for the utilisation of gas microturbine in the grid connected mode.

Due to the flexibility of GMT systems, the GMT market was valued at USD 40.5 million in 2015 and is growing to meet USD 101.3 million by 2024 with a CAGR of 10.8% [139]. With efforts in providing CHP subsidies in various countries and regions such as US [140], Japan [141], Europe [142], New Zealand [143], China [144], Malaysia [2], the potential of micro CHP is evident due to low investment cost, high energy efficiency and easy installation [65]. Moreover, by integrating GMT into microgrids, consumers can enjoy huge savings due to no transmission power loss, retain ownership of energy generation assets, unaffected by centralized grid problems, control local voltage, improve energy security and allow for higher penetration of renewable generation [145]. The agility of GMT-based microgrid systems is another distinct advantage. Due to the short delivery time of GMT [127], GMT-based microgrids can operate in a very agile manner. This means that GMT-based microgrids can very effectively cycle between islanding mode and peak shaving mode to leverage maximum economic potential from the grid ([118,146]), even with small capital investment.

Apart from having a well-designed microgrid physical system, the control and demand response program within the microgrid is also critically important (see Figure 8). Wang et al. [147] mentioned that the reliability and economics of microgrids can be drastically affected by upstream faults, improper control strategy and load uncertainty. These problems in microgrid control can cause power shortage and unstable power supply which ultimately affect the economics of the system. Rajarajeswari et al. [148] discussed that an unstable microgrid can increase customer outage costs and operation costs, affecting about 9% of total savings. Xiu et al. [149] showed that GMT can easily be controlled within the dynamic nature of microgrids even with a simple droop control strategy. Similarly, a double sinusoidal pulse width modulation (SPWM) control strategy was also proposed by Wei et al. [150] using dynamic simulation showing that GMT can maintain stable operation under load uncertainty in a microgrid. This highlights the good controllability of GMT due to its fast delivery time, stable operation and reliable outputs. Works of Vachirasricirikul and Ngamroo [151] exploited this property of GMT and proposed a robust controller design for microgrid systems that deals with uncertainty due to plug-in hybrid electric vehicles. A key challenge for process control within microgrids is during the transition between islanding mode and peak-shaving mode or vice-versa [152]. This is the timing where power outage is most probable. Researchers like Madureira et al. [153] proposed using a secondary load-frequency control to solve this problem. With higher levels of load-frequency control, Che and Shahidehpour [154] demonstrated the operational economics can be improved by resilience hierarchical control for DC microgrids. Later, Palizban and Kauhaniemi [155] demonstrated the effectiveness of using hierarchical control between island and peak-shaving modes in microgrids. Implementation of control design for microgrids in Hailuoto island [156] demonstrated an adaptive protection feature which adds a grid synchronization step to the control logic to transition between islanding mode and peak-shaving mode. Nevertheless, due to the excellent dynamics of GMT, controllability under such uncertainties in a GMT-based microgrid can be effectively responded to with high accuracy [125].

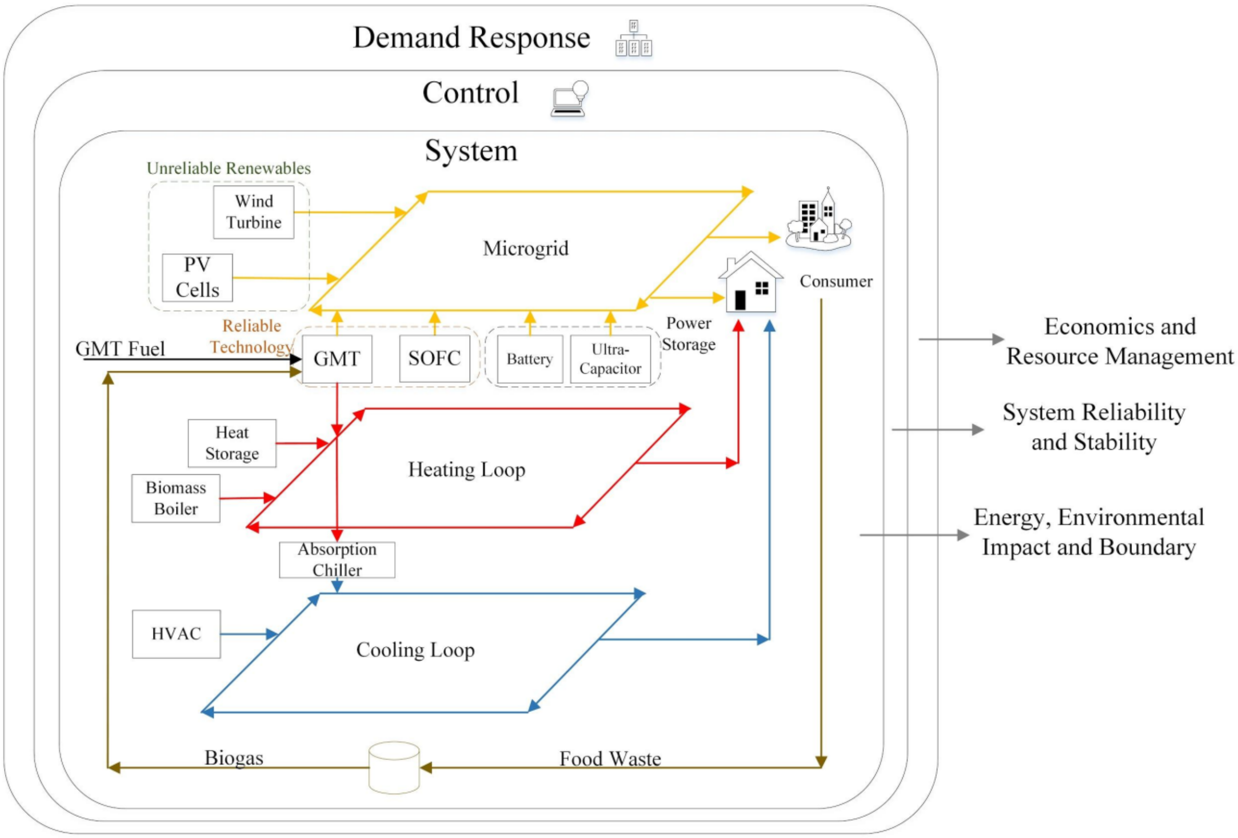


Figure 8: GMT-based Microgrid system, control and demand response

The demand response system within a microgrid operates to decide when to store energy, connect to the other grids, to enter island mode and other resource management operations [157]. Advantages of utilising a GMT-based microgrid does not only stop at the control level, but it also extends to the demand response level. Che et al. [158] demonstrated that GMT-based microgrids are excellent in islanding, emergency demand response, load restoration and synchronization of the microgrid with the utility grid. GMT within a microgrid can also operate as a fast backup energy source for operational management, Moghaddam et al. [19] demonstrated the possibility of applying multi-objective optimization for this purpose. In the multi-objective optimization study by Mohamed and Koivo [159], the consideration of emissions (in terms of NO_x, SO_2 and CO_2), safety, customer demands and economics was considered in a GMT-based microgrid that allowed for energy storage. Evolutionary optimization techniques such as an adaptive modified Firefly Algorithm was also used to improve GMT-based microgrid [124] where uncertainty can be modelled stochastically and operational economics can be improved in the long term. A GMT-based microgrid that includes fuel cells, wind turbine and PV array is also optimized using genetic algorithms for faster computation time by Deng et al. [160]. In the work, the GMT-based CHP in the microgrid was key in elevating the microgrid economics due to the utilisation of heat energy. The supremacy of using GMT within microgrids is beneficial towards economics, system control, resource management, system reliability, environmental emissions, system integration and ease for implementation.

4. Challenges and perspectives of GMT systems

Due to GMT being a highly flexible micro energy generation system, the environmental impacts of the power generation highly depends on its system integration, fuel usage and many other aspects. Life cycle assessment (LCA) studies for GMT technologies in different system configurations is one of the most solid methods to benchmark the environmental impact of GMT systems throughout its operational lifecycle. Although authors like Canova et al. [161] have studied the emission of GMT during different operation modes, GMT integrated systems are rarely studied using proper LCA procedures. Some related works in this field can be found in Table 2. Nevertheless, more LCA research is required in this field to properly gauge the environmental impacts of GMT-renewable integrated systems, advanced industrial processing applications, distributed generation and integrated microgrid systems. It is highlighted that due to load reduction affecting emission composition and power generation efficiency [162], GHG emissions are commonly reported with respect to a functional unit (ie. kg CO_2 eq/ kWh).

Table 2: Preliminary works of LCA in GMT systems

Work	**System**	**GHG emission (kg CO_2 eq/ kWh)**
Canova et al. (2008) [162]	Natural gas-fed GMT	(i) 1.01 (50% load) (ii) 0.84 (75% load) (iii) 0.77 (100% load)
Kimming et al. (2011) [163]	Produced biogas from Ley and Straw, then fed to GMT	-0.023
Meneses-Jácome et al. (2014) [164]	Biogas from wastewater treatment was fed to GMT	-0.085 to 0.123 (depending on production utilisation and energy avoidance)

Strazza et al. (2015) [165]	Biogas fueled GMT (not considering carbon mitigated, consider manufacturing, disposal, operation and maintenance)	0.699
Rillo et al. (2017) [166]	Natural gas-fed GMT	0.7
Zampilli et al. (2017) [167]	GMT with external biomass furnace	-0.34

The performance of GMT is influenced by the temperature of ambient air and its humidity as it is studied by Kanbur et al. [168]. Authors showed the impact of various temperatures and humidity levels on the power and heat generation and efficiency of the GMT. A more significant influence on the overall presentation of the GMT has the temperature, according to the study by Caresana et al. [169], 1 °C increase above the 15 °C (ISO condition) can decrease the electrical power production by 1.22% and the thermal power by 0.1%. Even though the numbers are low for smaller applications in a hot climate, it can make a difference in the design of the system and its operation. The humidity has an even smaller impact on the power production rate of the GMT, only about 0.05% with the change from 60% RH to 90% RH. However, it harms the CO_2 emissions – with the same relative humidity change there is 0.04% rise in CO_2 production. On a larger scale, this fact can cause a negative impact on GMT operation and meeting the strict limits of produced emissions. Also, in this area, further research is needed to establish the overall effect on the environment.

5. Future directions

The future of GMT within the context of distributed generation and microgrids remains promising as renewable sources require an alternative source which responds fast (in terms of systems dynamics) and is reliable [88]. Due to increasing market demands and expiring technological patents, the economics for GMT in microgrids has gradually improved over the years and will continue to do so [37]. On top of this, many countries are providing renewable energy and combined heat and power-related incentives for microgeneration. Microgrid operators can not only enjoy the benefits from peak-shaving, but also monetary advantages from policies and subsidies. Nevertheless, more research effort in the integration of GMT with renewable systems is required to improve energy efficiency, environmental impacts and make operations seamless. Also, some research on improving the construction materials within GMT should be carried out (e.g. nano materials, enhanced ceramics and polymers) to improve unit total efficiency and allow for a larger variety of multi-fuel inputs to be fed into the GMT system. The future of GMT and energy storage is also a pathway that is worth much more attention as GMT can also act as the primary renewable source which functions to meet varying demands within a microgrid. Such interaction and integration between GMT and various types of energy storages would provide better energy efficiency and demand-response operations [19].

6. Conclusion

This paper has showcased the recent approach to the gas microturbines as a source for industrial application and as part of comprehensive microgeneration systems. The development of local power production is a modern and favourable way to create a stable and sustainable decentralised generation system. The main focus is on the reliability of the system; the GMT is highly effective with regular operation time above 25,000 hours and proved to be a convenient source for a wide range of application. Also, the GMT is progressive technology able to utilise renewable sources such as biogas, landfill gas, flare gas, etc. Furthermore, the GMT can be coupled with renewable technologies like solar PV, wind turbine or fuel cells to create hybridising and reliable system ready to operate in almost any condition. The majority of studied papers have the CHP efficiency of about 80-90% with GMT use. Next aspect is the economic feasibility of such systems, the investment cost for GMT is still high. However, a large number of countries provide the CHP/CCHP operators with beneficial tariffs or subsidies.

Some can argue there is power loss in decentralised generation technologies. However, microgrid with GMT supports the operation in remote areas, island operations and helps with the peak-shaving and stabilising the market prices. Also, the local power system can better react to renewable fuels and implement new technologies. Of course, it is important to accurately control the system, especially in case of connecting to the main grid and to respond to demands, all to provide adequate energy security. Therefore, GMT is easily operated with low maintenance and good controllability, which makes the gas microturbine suitable prime mover.

Another advantage of GMT is widespread of industrial, rural and commercial applications. All of these aspects can be employed for local microgrid according to the requirements. On the other hand, there is still space for GMT to improve and provide the applications with low-cost combined power generation and make the systems viable.

Acknowledgements

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