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Trends and advances in micro gas turbine technology for sustainable energy solutions: A detailed review

A.H. Samitha Weerakoon *, Mohsen Assadi

Faculty of Science and Technology, University of Stavanger, Kristine Bonnevies vei 22, 4021 Stavanger, Norway

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A B S T R A C T

Micro Gas Turbines (MGT's) have gained significant popularity in various energy systems due to their adaptability, low emissions, flexible structure, and ease of maintenance. Past two decades, Micro Gas Turbine (MGT) based multidisciplinary research has increased. Various sectors of multidisciplinary research and development incorporate theoretical, numerical, and experimental methods, combining classical and innovative technologies to enhance performance and compactness. With growing interest in NH_3 and H_2 as fuel to reach goal on zero-carbon emissions, MGTs have gained excessive interest as ideal candidate due to fuel flexibility. This detailed review on multidisciplinary research of MGTs, analyzes twelve (12) sub-research branches, provides detailed systematic review on each technology field, updated data and logical conclusions identifying areas that are most influential with MGTs, towards a sustainable, zero-carbon future, and indicate areas descending and fade off with time. Current progress, advances of MGTs sector are analyzed, including latest case studies, along with their components, development status, applications, performance factors and notable explorations. Analysis includes various numerical and experimental approaches alongside conventional workflow architectures and optimization algorithms developed for MGTs. Later, the paper highlights MGTs operating with alternative fuels, new combustion chamber developments, advances in combustion kinetics to suit micro-scale architecture to facilitate biofuels, unconventional fuels. Further extensive analysis stretches further to ammonia (NH_3), hydrogen (H_2), and various other fuels applied with MGTs, identifying performance, challenges and solutions associated with their use. The identified research gaps and recommendations are outlined in this paper to assist future researchers and industry experts in gaining a broader understanding of MGT technological trends.

1. Introduction

Gas turbine technology evolved since the development of first 370 kW gas turbine in 1920 s [1,2], leading to emergence of Micro Gas Turbines (MGTs). MGTs are small-scale gas turbine engines offering low emissions and efficient electricity generation, suited for various applications [3–5]. MGTs function conjunction with renewable sources or as standalone units in off-grid operations [6,7]. MGTs are fuel-flexible, capable utilizing Natural Gas (NG), biogas, and hydrogen, but each fuel type demand unique combustor [8]. MGTs famous with low noise,

Abbreviations: MGT, Micro Gas Turbine; ICE, Internal Combustion Engine; DEG, Distributed Electrical Power Generation System /Decentralized Energy Generation System.; DGS, Distributed Generation System; CHP, Combined Heat and Power; CCHP, Combined Cooling, Heating and Power; CGS, Cogeneration System; TGS, Trigeneration System; EFmGT, Externally Fired Micro Gas Turbine; CBC, Closed Brayton Cycle; RBC, Recuperated Brayton Cycle; CSP, Concentrated Solar Thermal Power; PV, Photo Voltic; TIT, Turbine Inlet Temperature; CFD, Computational Fluid Dynamics; GHG, Green House Gas; GHGE, Green House Gas Emission; DNI, Direct Normal Irradiance; SE, Sterling Engine; TESS, Thermal Energy Storage System; REEV, Range Extended Electric Vehicle; MGTRE, MGT based Range Extender; ICERE, Internal Combustion-Engine-based Range Extender; PMSG, Permanent Magnet Synchronous Generator; LHSS, Latent Heat Storage System; AHAT, Advanced Humid Air Turbine; LES, Large Eddy Simulation; LHV, Low Heating Value; LPG, Liquefied Petroleum Gas; CC, Combustion Chamber; FUF, Fuel Utilization Factor; FVM, Finite Volume Method; FEM, Finite Element Method; SOFC, Solid Oxide Fuel Cell; WWTP, Waste Water Treatment Plant; TGS, Tri-Generation System; ABS, Absorption Chiller; COP, Coefficient of Performance; IRR, Internal Rate of Return; NPV, Net Present Value; DCF, Discounted Cash Flow; LCOE, Levelized Cost of Electricity.; NG, Natural Gas; GA, Genetic Algorithm; CC, Carbon Capture; DHN, District Heating Network; DCHP, Domestic Combined Heat and Power; CCP, Combined Cold and Power; CGS, Co-Generation System; MOOP, Multi Objective Optimization; HRR, Heat Recovery Rate; U_f, Fuel utilization factor; Φ, Equivalence ratio.

* Corresponding author.
E-mail addresses: abeysingha.h.weerakoon@uis.no (A.H. Samitha Weerakoon), mohsen.assadi@uis.no (M. Assadi).

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ease of operation and reliable making them ideal for Decentralized Energy Systems (DES) [10–15]. Combining MGTs with Renewable Energy Sources (RES) significantly reduce CO_2 emissions, mitigate fossil fuel depletion rate and global warming [9,10]. Concept of Decentralized Energy Generation (DEG) gained popularity with RES advancements and potential to decrease emissions and costs promoting energy system resilience [11–14]. MGTs are an attractive choice with compactness, small size, high energy efficiency, and fuel flexibility, leading to applications in DEG, waste heat recovery (WHR), CHP, CCHP, and as range extender for EVs [15–20].Table 1.

Advances in MGT technology is vivid and widespread across many engineering disciplines. Latest advances and progress in MGT sector require a review based on knowledge, identifying challenges, and exploring future developments, helps to identify future trends in MGT based multidisciplinary research [21–30]. Cohabitated research on MGTs involves many sub engineering branches, thus a systematic review across theoretical, numerical, and experimental categories, relying on first principles, theoretical and experimental work combinedly provide much broader perspective on technological level and capacity to grow for MGTs. Computational calculations or simulations play an important role utilizing 0D/1D methods-based simulations solving complex multibody, Multiphysics design concepts related MGT developments. Numerical simulations are mostly validated with experiments to preserve research output accuracy. Past decade MGT based development trends utilized software tools like Aspen Hysys, Aspen Plus, FlowNEX, IPSEPro, HOMER pro, MATLAB, Python, or C++ for solving complex simulations, some researchers prefered advanced commercial software's such as Ansys CFX ®, FLUENT ®, and COMSOL, and others preference based on open-source software [31–47].

This article conducts a systematic review of MGT-based multidisciplinary research advancements and case studies to identify their future trends. However, due to Covid-19 pandemic, post pandemic and ongoing Ukrainian war has emerged as formidable global factors significantly influencing energy trilemma worldwide, it can be seen a sharp decline in research work related with MGTs (Fig. 1[b]). This detailed analysis and systematic review-based aim to identify reasons behind this decline and explore sub-branches of MGT research that would hold potential for sustainable energy-focused future. The concept of multidisciplinary research based on MGT revealed a pattern, with major portion of research contributions coming from several renowned pioneers of MGT based multidisciplinary research (Fig. 1[a]). The "Scopus" curve of interest in MGT, representing the number of published papers under "Micro Gas Turbine" keyword over time, and research

Table 1
Comparison of previous review papers specific application area on multidisciplinary research with the present article. (Details included in **Appendix A** to conceive the length of article).

MGT Based Review Papers Specific Application area on Multidisciplinary Research Framework															
Study [Reference number]	Component				Applications										
	Compressor	Turbine	Combustor	Recuperator	CSP	DEGS/CHP/CCHP	WHR	MOOP	ANN/ML	REEV	SOFC	Non-Biofuels	Biofuels	Numerical Tools	H_2 and NH_3 as Fuel
[13]	X	X	X	X						X	X				
[14]			X	X				X							
[15]		X		X			X	X							
[16]				X				X							
[17]			X										X		
[18]													X		
[19]												X	X		
[20]						X			X						
[21]						X		X	X						
[22]														X	
[23]						X									
[24]	X	X	X	X	X	X				X	X		X		
[25]			X	X											
[26]									X				X		
Present Paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

network's clustering surrounded by several other keywords such as "combustion", "combustor", "radial turbines" which are sub fields of MGTs, shows spreading pattern (Fig. 1[c]) of important key words to identify a root cause analysis. Analyzing this research network and sub-branches, twelve (12) subgroups identified and analyzed, this paper presents progress and trends in each sub-group. In the context of previously published "review articles on MGTs," Table 1 provides a comparison while a detailed summary with Annex I for side-by-side comparison. Unlike previously published review papers, which are focused on specific component or a characteristic with a biased perspective of MGTs to promote a particular concept, this paper.

approaches and analyzes all MGT-based technological improvements in a holistic manner, in the order of descending year of publication. This article strongly aims to provide a comprehensive and authoritative resource on multidisciplinary research on MGT technology, consolidating knowledge and guiding future research. The focus will be on assisting advances in sustainable energy solutions, aligning with UN Sustainable Development Goals 7 and 13, which emphasize affordable and reliable energy access and combating climate change. The objectives include consolidating diverse findings, guiding future research, assessing technology advancements, and contributing to sustainability and energy transition by highlighting MGTs' potential for energy efficiency, renewable integration, and decarbonization.

2. MGT technology

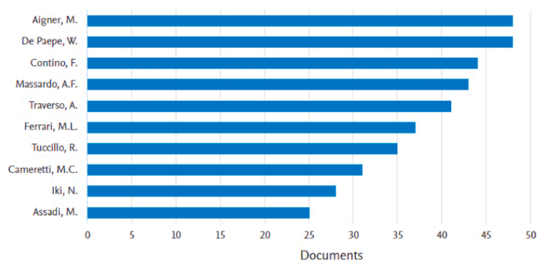
Applications of MGTs expanded to diverse fields, prompting advancements in related components; Refer Fig. 2(c) as multidisciplinary fields of MGT research and sub divided into twelve (12) segments. These segments identified based on Fig. 1 (c) MGT research landscape.

2.1. Concentrated solar thermal (CSP) energy and PV

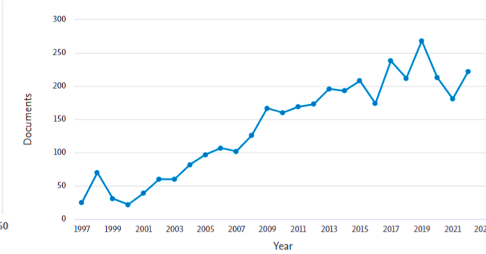
SCP systems garnered interest due to efficiency and cost-effective heat storage capability [48]. During 1980 s, the United States witnessed design and testing of solar-mercury thermal power system employed GTs as power generators [49]. Aichmayer et al. (2014) [48] designed a solar receiver for small-scale hybrid solar-MGT, achieving thermal efficiency 86.7 % with pressurized configuration receiver placed before the turbine. Carmelina et al. (2017) [53] compared two MGT-CSP layouts, in Fig. 3(a and b). Layout (a) features parabolic trough network with ORC system, layout (b) involves solar tower for direct air heating. Both layouts based on 30 kW MGT. Pressure losses in recuperator and combustor, with different inlet temperature levels in both layouts, found using numerical modeling. Layout (a) enhanced power output and allowed for heat recovery, layout (b) achieved immediate fuel energy savings (increased FUF) and higher net efficiency. Both layouts reduced CO_2 emissions, but number of grouped components synchronized in solar systems are extremely high, resulting in higher initial cost and higher maintenance costs, require complex control system, which are working drawbacks.

Stefano et al. (2018) [54] developed a simulator for dish mounted MGT (In Fig. 3(c)) under Project OMSoP, providing high-fidelity replica of real CSP power plants, based on study [53] using normalized performance maps for turbine and compressor to predict performance under different DNI conditions, they found recuperated MGT efficiency is 22 % higher with TIT at 800 °C. This simulator algorithm prioritize efficient, low CPU usage, memory occupancy. Modular illustrated in (Fig. 3(d)), outlining algorithm architecture, aimed at achieving optimized solutions. This program compared Stirling Engines (SE's) with MGTs. MGT offered higher reliability and lower maintenance costs, increasing overall CSP performance when solar concentrator efficiency dropped below 60 %. intricate optical system negatively affects performance of CSP-MGT plants. Ahmadi et al. (2018) [55] reviewed CSP-MGT plants, found that 10 % increase in turbine efficiency results 6 %-12 % of η_{all} improvement, using Supercritical CO_2 led to higher cycle

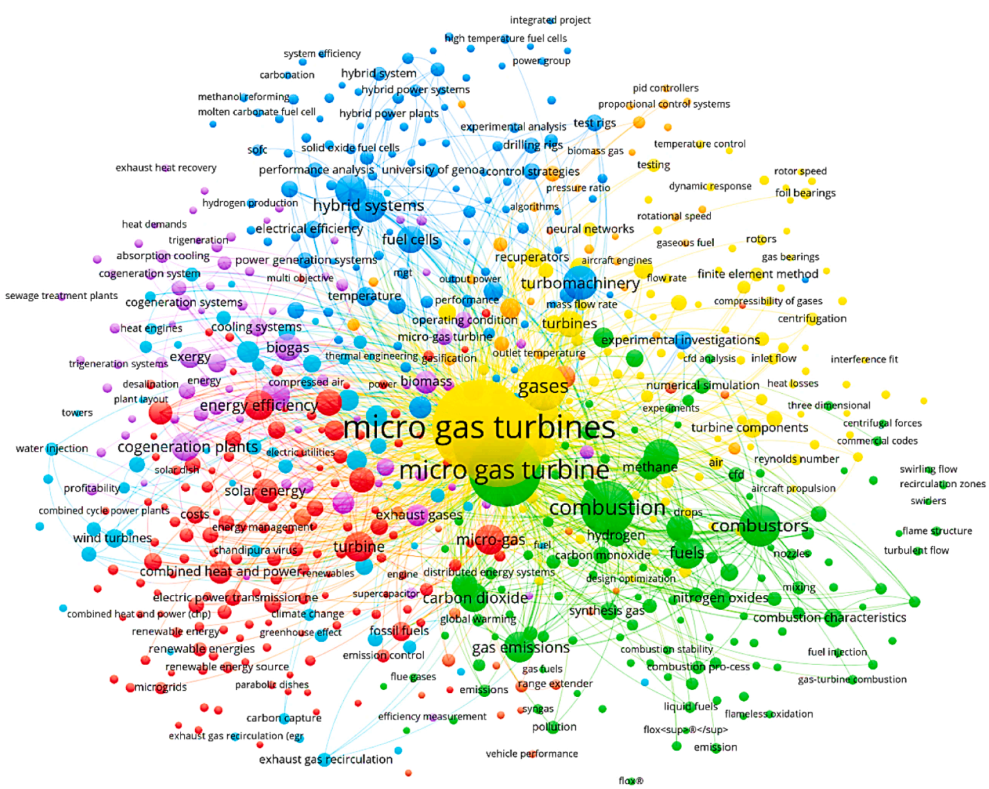
MGT Based Review Papers Specific Application area on Multidisciplinary Research Framework															
	Component				Applications										
Study [Reference number]	Compressor	Turbine	Combustor	Recuperator	CSP	DEGS/CHP/CCHP	WHR	MOOP	ANN/ML	REEV	SOFC	Non-Biofuels	Biofuels	Numerical Tools	H_2 and NH_3 as Fuel
[13]	X	X	X	X						X	X				
[14]			X	X				X							
[15]		X		X			X	X							
[16]				X				X							
[17]			X										X		
[18]													X		
[19]												X	X		
[20]						X			X						
[21]						X		X	X						
[22]														X	
[23]						X									
[24]	X	X	X	X	X	X				X	X		X		
[25]			X	X											
[26]									X				X		
Present Paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X



(a)



(b)



(c)

Fig. 1. (a) MGT based multidisciplinary research published on a yearly basis from 1997 to 2022 (b) MGT based multidisciplinary research work by major researcher with number or publications, (c) Scientific landscape of MGT based multidisciplinary research from 1997 to 2022.

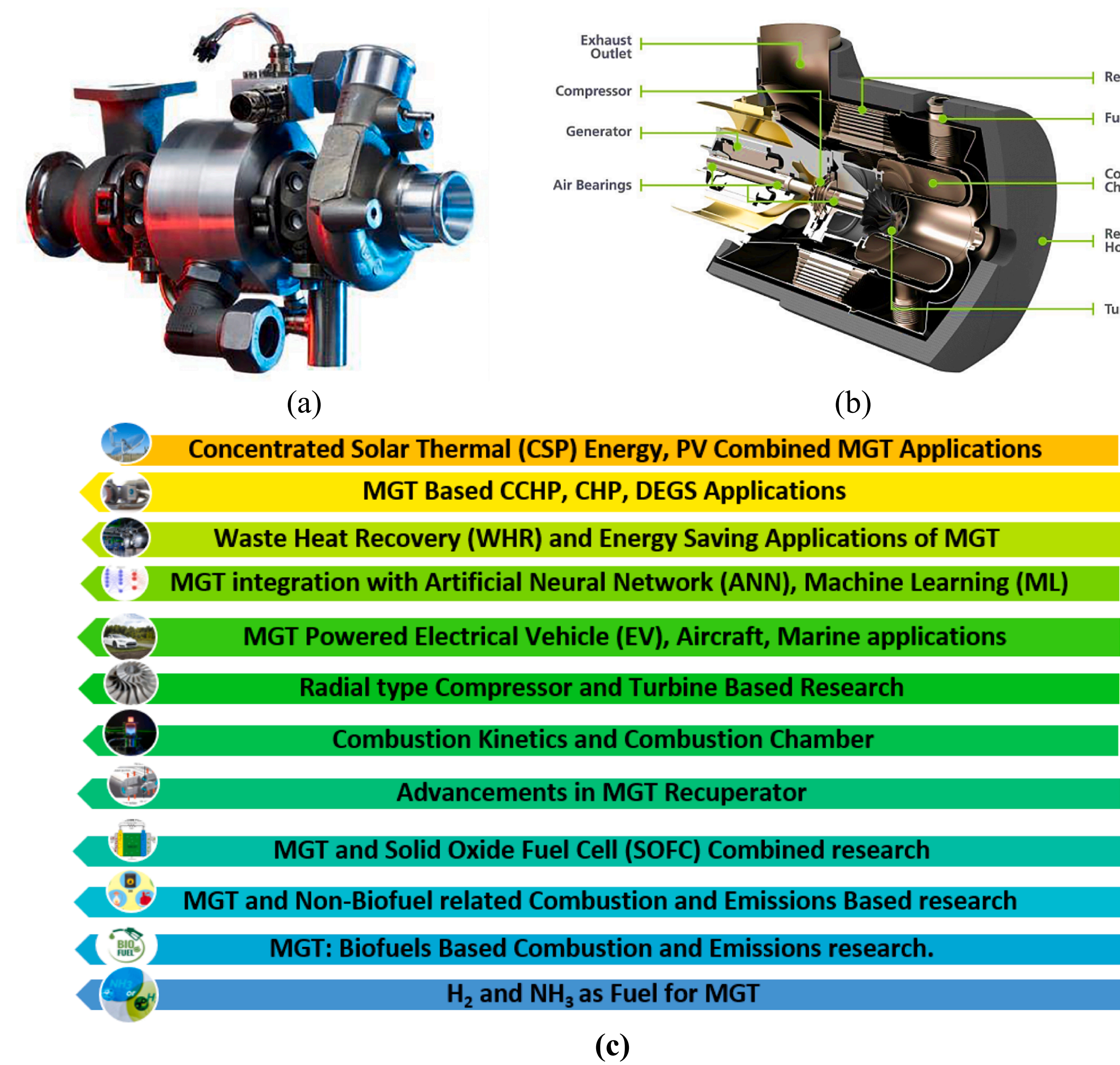


Fig. 2. (a) MTT's micro gas turbine assembly (b) MGT system components by Oppong, Francis et al., (2017). "An overview of micro gas turbine engine performance investigation" and (c) Multidisciplinary fields of MGT research.

efficiency. Davide et al. (2018) [56] proposed "honeycomb" TES based numerical model for CSP-MGTs, showing 11.7 % increase under daily energy generation and efficient smoothing of solar fluctuations. Brian et al. (2019) [57] developed a theoretical MATLAB model for CSP-MGT, achieving 20 kW nominal work output and 8 % cycle thermal efficiency (η_{th}) increase (without recuperator). Recuperation improved η_{th} by 20 %. Jinli et al. (2019) [58] used MATLAB-Simulink for dynamic simulation, achieving average system efficiency (η_{sys}) 24.1 % with peak solar energy contributing 64.7 %. Further analyzed system's responses under varying load and solar irradiance conditions. Solar integration which further reduced fuel consumption negatively affected with combustion instabilities. Adjusting heliostat orientation and load management proposed for stable operation. In Fig. 4, MGT T100 model's performance under steady-state conditions validated using experimental data using original research work form DLR (German Aerospace Research Center), involving grid-connected operation at typical ambient conditions. This validation acts as quality control between simulation results, when actual performance was of a real system predicted based on actual data. This concept of MGT component validation was lacking with previous literature studies. The detailed matching of the model with reference segment enhanced MGT performance test data during case studies.

This comparison involved variables as compressor, turbine, and recuperator temperatures and pressures, air mass flow rate, power output, and generation efficiency. Maximum relative error 5.7 % of recuperator exhaust side temperature. Experimental validation confirms model's accuracy, simulated components actual data indicating TES significantly reduces combustor temperature fluctuations. This method is useful for adaptation in future work having similar analogy. Mauricio B. et al. (2021) [59] compared Rankine and Brayton air standard cycles for 30 kW Steam Turbine (ST) and 30 kW biogas powered MGT in small-scale solar-bio-hybrid system. ST had higher global efficiency (67.7 %), MGT showed better η_{el}(27.0 %), In Ref [59] paper, "Table 1″ provides system information. They evaluated impact of different climates for MGT-CSP and ST performance. However, experimental validation not provided, further analysis could optimize similar types of small-scale

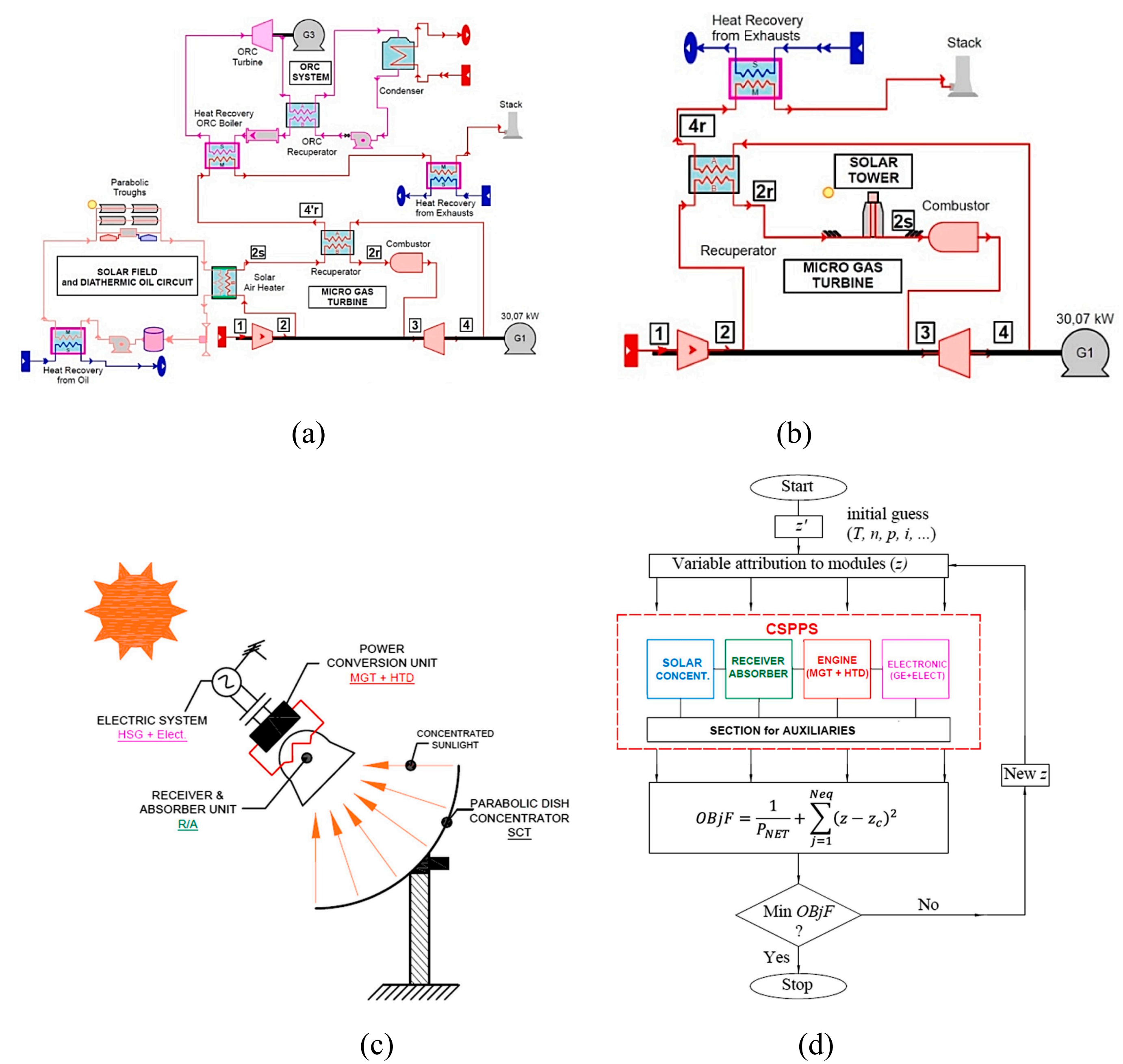


Fig. 3. (a) MGT-ORC power plant with the solar array integration (b) MGT power plant with the solar tower integration [53], (c) Layout of the dish-MGT CSP plant and (d) CSP plant simulator modular structure and ECRQP solution algorithm [54].

hybrid-RES following Ref [59] methodology. Future focus can consider exploring scaling effect of ST and MGT array layout for cogeneration. Michela L. et al. (2022) [60] developed quasi-steady-state numerical model for 5–7 kWe solar parabolic dish-MGT pilot plant, Italy. Volumetric receiver outperformed cavity system, generating average output power 3.58 kW. System's maximum power output reached 5.6 kW during short transients, limited factor being stator current. Annual average η_{cycle} ~ 17 % (vs. 21 % targeted), global efficiency (η_{global}) 5.2 % to 5.9 %. Increasing 900 °C TIT improved η_{cycle} to 31 % and η_{global} to 19.8 % under design conditions. Capacity factor varied 0.19 to 0.22, over 35 % in solar-favorable locations. Optimizing solar dish and upgrading auxiliary components potentially double system power output at 10kWe with 80 % optical efficiency. Overall, integration of CSP with MGTs shows potential for efficient power generation, but most adopted methods are not cost-effective and flexible under real operation. Advantages include higher reliability of MGT, lower maintenance compared to SE's and using sCO_2 enhancing $\eta_{overall}$. MGTs have better electrical efficiency than scaled-down ST's integrating with CSP. However, practical limitations like high initial capital costs (CAPEX), land requirements, intermittent solar energy, efficiency losses impact economic viability and performance. Skilled maintenance, operation needed, thus making challenges in regions with limited technical expertise. These systems heavily depended on solar irradiance, making them suitable with high solar resource regions. Challenges in solar concentrator precision, optical system calibration (detailed in EU funded OMSoP Project), susceptibility to dust and soiling exist as recent practical difficulties for CSP-MGT implementation. Combining these limitations, CSP integrated MGT based research activities have less interest for further research and development, this sector has limited prospects in future when competing with more affordable and less

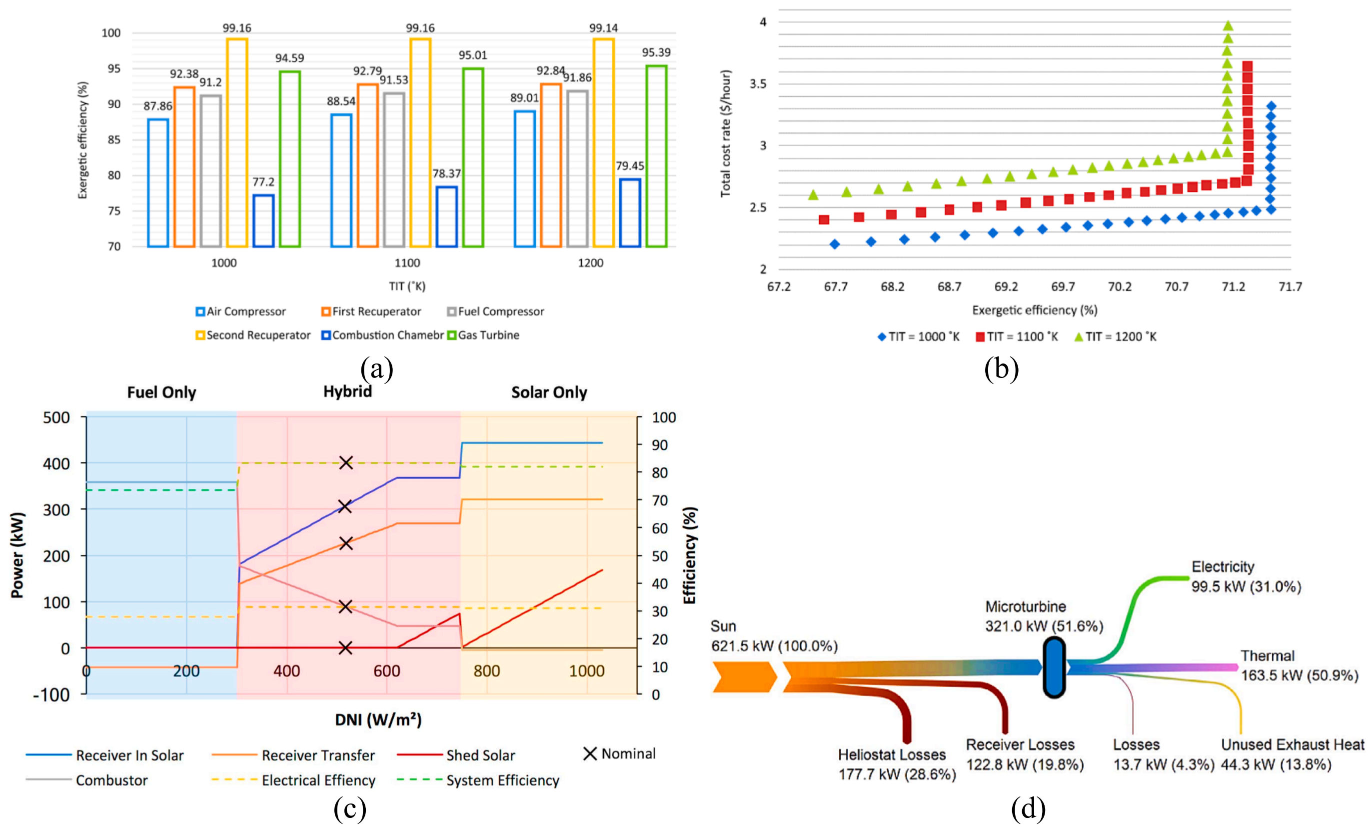


Fig. 4. (a) Variation of η_{exer} with TIT for each component of system (Compressor pressure ratio optimized in each TIT as 4, 4.75 and 5.4), (b) Distribution of Pareto optimal points solutions for η_{exer} and total cost rate of CHP system [76], (c) Heat transfer rates of solarized MGT operating rated load under ISO conditions for varying DNI and operating modes (d) Solarized-MGT operating in solar only mode without shedding (DNI 750 W/m^2) [78].

complex MGT based power generation systems.

2.2. MGT assisted combined cooling heating and Decentralized power generation (CCHP, CHP, DEGS) applications

Cogeneration (CGS) or trigeneration (TGS) systems offer simultaneous generation of electricity, heating, and cooling from single energy source. m-CHP involves various prime movers, SE, reciprocating engines (ICE or CE), steam engines (STE), GT's, MGT's and ORC. These systems integrate with RES like biomass, solar, wind, and geothermal, providing versatility and sustainability. Small-scale power production using gas engines, MGTs, fuel cells particularly efficient with their high performance at low power outputs [61–63]. S. Murugan et al. (2016) [64,65] compared m-CHP integrating several prime mover types. Table 2 compares various prime movers used for m-CHP. MGTs offer advantages over ICEs, such as fewer moving parts, better fuel adaptability, and lower emissions, easy to maintain and compliant with strict emission standards. MGT's exhibit higher thermal to power density and exhaust gas temperature compared to FCs, ORC systems, SE's, making MGT suitable for efficient polygeneration.

SOFC's have lowest heat-to-power ratios at 1:1, ICEs, and SEs 3:1 and 8:1. Apart from technical parameters, an economical assessment for CHP by Gabriele Comofi et al. (2014) [66] analyzed various technoeconomic (TEA) indicators using different prime movers. MGTs showed lowest variable O&M costs, moderate investment costs per MW. Incorporating TES with CHP reduces dependence on centralized heating. As a trend, MGTs and SEs are key players making m-CHP market attractive due to their lower investment costs, better value due to high thermal to electrical energy ratio. In Ref [66] paper, "Table 6″ provides summarizes key economical values for m-CHP used in commercialized projects. Similar

Table 2
Comparison of mCHP prime movers and their features.

Description	SE	ICS	MGT	ORC	SOFC
Recoverable heat	–	15–30 %	45–55 %	45–65 %	25–35 %
Co-generation efficiency	65 %–90 %	60 %–80 %	60 %–90 %	65 %–80 %	60 %–90 %
Thermal efficiency	75 %	64 %	60 %	–	40 %
Electrical efficiency	10 to 20 %	20–40 %	15–30 %	~ 10 %	30–70 %
Total efficiency	65–95	50–80(SI)	60–80	65–80	60–80
Power to heat ratio	0.2	0.38	0.33	NA	1
Heat input / Combustion	External	External	External	External	Electrochemical
Maintenance	–	<1000 h	>8000 h	150–250 h/year	–
Source of heat input	HC, waste heat, H_2	HC, H_2	HC, Biofuels, waste heat, H_2	HC, waste heat, H_2	NG, Biogas, H_2
Respond to load change	Low	Faster	Faster	Faster	Faster
Initial investment	Low	Low	700–900 euro/kW	High	High
Emission, NO ppm	Nil	<100 ppm	<10 ppm	Nil	<10,000 ppm
State	Developmentary early market	Widespread	Uncommon	Development, early market	Proven Technology

studies with varies numerical and experimental data extended in [67–75] studies. J. Pirkandi et al. (2015) [76] optimized MGT- CHP cycle using Genetic Algorithm (GA) using MATLAB, considering economic parameters. In Fig. 4(a) combustion chamber exergetic efficiency (η_{exer}) comparatively lower than other components, enhancing η_{exer} achieved by raising TIT's (T_3 and T_4). However, practical constraints related to turbine material and costs, restricts significant temperature adjustments. Thus, increasing T_3 and T_4 for better η_{exer} shift design point from optimal state to alternative working point causing objective function to minimize. Further, considered 3-TIT's (1000 K, 1100 K, 1200 K) and varied compressor pressure ratio (P_r). η_{exer} increased 67.69 % to 71.52 % with 1000 K TIT, total cost rate increased 2.20 to 2.57 ($/h). In Fig. 4(b), further TIT increment increased cost rate to 3.32 at 71.53 % efficiency. This research work highlights decision-making process for these systems, based on individual preferences is crucial when selecting final optimum solution from Pareto frontier.

With using Multi-Objective Optimization (MOOP) selection of the optimal solution requires decision-making process based on individual preferences. Each point on Pareto solution represents an optimized set, system operators might choose different points as optimum solution based on their requirements and cost budget. Y.-j. Xu et al. (2015) [77] analyzed steady-state CCHP performance. They developed numerical model for MGT and LiBr-H_2O single-effect ABC with cooling tower to study off-design performance. System performance influence by MGT under varying load condition, emphasizing importance of selecting system parameters optimized for CCHP mode to ensure optimal performance. J. Nelson et al. (2017) [78] developed a quasi-steady state thermodynamic model for 100 kW_e/165 kW_{th} solarized-MGT unit working CHP. Model achieved close agreement with commercial systems under ISO conditions. Simulations indicate, η_{el} of 31.5 % and $\eta_{overall}$ of 83.2 % with DNI: 515 W/m^2. Under different operating conditions, system reduced NG consumption 26.0 %. Achieved 28.4 % reduced NG consumption. Fig. 4(c) indicates how solarized MGT system adjusts operation based on DNI. Shifting from fuel-only to hybrid mode as DNI increases, achieving peak efficiency at 71.4 %. At 750 W/m^2 DNI operates exclusively on solar power. Fig. 4(d) analyzes energy losses

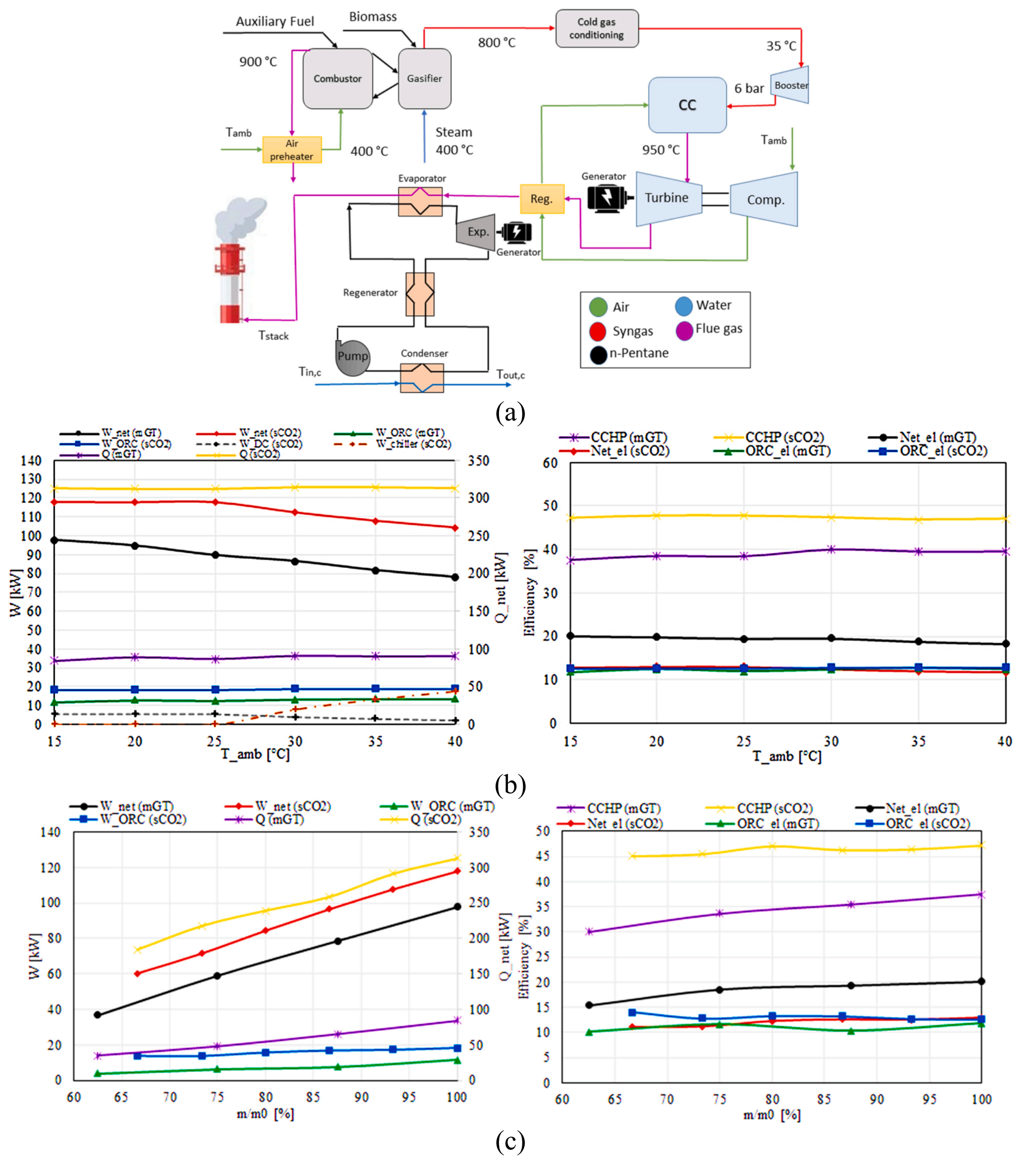


Fig. 5. (a) The process diagram of the sCO_2 + ORC system (b) Electric and thermal power (left) and efficiencies (right) by the ambient temperature at the nominal mass flow rate, T_{stack} at140 °C, and $T_{in,C}$ at 60 °C, (c) Net electric and thermal power (left) and efficiencies (right) by the turbine mass flow rate at T_{amb} at15 °C.

under different modes. Inconsistencies were observed in CSP system behavior across various conditions and operation modes. Even under fuel only, hybrid or solar only modes, CSP systems had inconsistencies. Considering portable applications for MGT-CHP systems as lifesaving appliance or as military protective kit, H. Adhami et al. (2018) [79] designed a single-person, portable m-CCHP system using MGT and micro-ABC, generating 500 W_{el} at 200,000 rpm and 50 °C. Hybrid electrical and thermal load strategy showed highest efficiency 29 % and lowest fuel consumption, SFC of 0.0645 gr·s^{-1} for LPG. Huailiang Y. et al. (2020) [80] assessed CCHP coupled with multi-effect desalination (MED) system using solid oxide fuel cell/micro gas turbine (SOFC/MGT) configuration. Conventional exergy analysis identified components with the most exergy destruction (afterburner, SOFC, and MED), components like inverters, MGT, and air compressors indicated potential for reducing exergy destruction. Ramin M. et al. (2022) [81] compared performance of MGT and supercritical CO_2 (sCO_2) systems coupled with bottoming ORC (In Fig. 5(a)). At full-load operation at 15 °C, sCO_2 system boosted 25 % higher net electrical power (P_{el}), 40 % higher $\eta_{overall}$, but 1.75x times more biomass consumption compared to base MGT. Concluded that sCO_2 system provide better performance under CCHP applications despite lower η_{el}. Referring Fig. 5(b), MGT system's P_{el} decreased as ambient temperature dropped thus lower air density affecting compressor mass flow rate. Conversely, sCO_2 system remained stable up to 25 °C maintaining compressor suction temperature. Beyond 25 °C, hiller activated alongside dry cooler to cool CO_2, ensuring 10 K temperature difference. Ambient temperature had minimal influence on ORC system's performance and thermal production. Interestingly in off-design conditions, in Fig. 5(c) turbine mass flow rate ($\dot{m}$) adjusted via adjusting shaft speed. Under partial load operations, system decreases net electric and thermal power. Net CCHP efficiency dropped for MGT system, while power reduction had marginal efficiency loss. When gasification agent changed, to air replacing steam, at 62.5 % partial loading, MGT P_{el} dropped to 62.3 % and P_{th} 58.8 %, sCO2 system dropped 53.1 % (P_{el}) and 41.2 % (P_{th}).

Integration of MGTs with DEGS, CHP, and CCHP systems holds promise for efficient energy generation. Ongoing research should focus on techno-economic analysis (TEA), energy and exergy balance analysis, optimization models for distributed cogeneration, high-fidelity studies like LES methods for component development, numerical simulations for off-grid and off-design performance, and portable, compact micro-CCHP systems. Research also explores integration with Renewable Energy Sources (RES), larger Thermal Energy Storage (TES) systems, load management, MOOP, off-grid applications, and connections to desalination, ABC, and heat pumps. This research area is critical in addressing climate change and increasing demand for cooling due to global temperature rise. CCHP and MGT-based research, especially with cooling systems like ABC, heat pumps, and cost-effective cooling methods, will dominate future research activities. This multidisciplinary field is at forefront of progressive trends, contributing to a more sustainable and resilient energy landscape.

2.3. Waste heat recovery (WHR) and energy saving applications of MGT

As demand for clean and efficient energy continues growing, role of MGTs in WHR and energy-saving applications become prominent. However, existing research on water injection in MGTs for WHR lacks a generic study to determine the optimal route for WHR and performance improvement [82,83]. W. De Paepe et al., (2014) [84] performed numerical simulations to determine optimal water injection settings for WHR-MGT using Aspen®. Injecting 17 % water achieved $\eta_{overall}$ increase 9 % at stack temperature 53 °C. Preheated water injection demonstrated highest increase in η_{el} by 4.6 % with lowest stack temperature 62 °C. A novel concept investigated by B. Dehghan B. et al., (2017) [85] integrated MGT and Ground Source Heat Pump (GSHP) with spiral Ground Heat Exchangers (GHEs) to cater heating demands in buildings. Concept was simulated using COMSOL CFD software. Existing GSHP, connected to 9-spiral GHEs, fulfills heating requirements. A new combined system was proposed, incorporating an MGT, a heat pump, shallow underground thermal storage, and additional spiral GHEs (No. 10–25) for WES. The proposed MGT supply the building's electricity demands, offer advantages in weight and space saving, reliability, low emissions, and flexibility in operation and low cost. Proposed MGT (In Table 3) supply the building's electricity demands, offering advantages with weight and space saving, reliability, low emissions, and flexibility in operation and low cost. Include use of spiral GHEs (No. 1–9) to store waste energy in the ground. These stored heat reserves are then extracted through GHEs No. 1–9 to meet heating needs. The matching of MGT specification with the GSHP needs careful consideration. This concept soon will gain more attraction with the bore-hole type underground heat systems. WHR based MGT research expected to grow as in future with the increase of MGT commercialization.

2.4. MGT optimization and integration with artificial neural network (ANN), Machine learning (ML) methods

While there have been numerous studies on the application of artificial neural networks (ANNs) for large-scale GTs, for MGTs, relatively fewer publications combined with ANNs, ML or AI. Few notable studies have explored the use of ANNs in context of MGT in literature. C.M. Bartolini (2010) [87] employed ANNs, Adaptive Network Fuzzy Interface System (ANFIS) to generate performance diagrams/maps for T100 MGT using experimental data from manufacturers. Model predicted MGT performance, emissions under various scenarios, enabling optimization of MGT for real-world installations. The data set did not cover entire operational range of turbine, validation resulted with high accuracy, with lowest coefficient of determination (R^2) ~ 0.9962, indicating trained ANNs ablility to reliably predict performance and emissions of MGT. Tools with highest accuracy and performance summarized in Table 4.

Data validations and set comparisons in Table 4 demonstrate suitability of trained ANN/ML methods to MGTs. The ANN successfully predicted power loss with increasing temperature with air density effects. Pressure and humidity have minimal impact on power. These relationships was confirmed by ANN results for fuel flow rate. The fuel LHV assumed in calculations despite possible variations. Similar ANN model by F. Kartal 2023 [88], accurately forecasts MGT output parameters with R^2 value > 0.99 and Mean Absolute Percentage Error (MAPE) < 1 %. H. Nikpy et al. (2013) [89] developed an ANN model for remote monitoring and diagnostics of MGT-CHP. Used experimental data from Turbec T100 MGT test rig. ANN, was multi-layer feed-forward network with back-propagation algorithm, achieved accurate predictions, with compressor inlet measurements proving essential for improved accuracy. Optimized input set included power, compressor inlet temperature, and pressure. Engine modifications (extra sensors and instrumentation Fig. 6. I (c)) had minimal impact on model accuracy, ANN model accurately predicted combustion chamber inlet parameters when the output data set was added. In Fig. 6 (II), the final model exhibited 0.56 % average prediction error. Power output prediction (Fig. 6. II (a)) demonstrated most errors < 2 %. Independent input parameters made it effective for condition monitoring, detecting component-level degradation, optimizing repairs, and estimating performance. The ANN model's simplicity and real-time prediction capability are advantageous for machine based "operator training" without expertise in MGTs or ANNs. Fig. 6. (I) (a) illustrates multi-layer feed forward network layout, (b) final model architecture, how the layers are formulated, each neuron is linked with subordinated feed-forward and backward layers.

Same author H. Nikpy et al. (2013) [90] evaluated the performance and emissions of a 100-kW commercial MGT fueled by mixtures of NG and biogas using experimental data, with an ANN model in predicting MGT's performance. Experimentally found that burning a mixture of NG and biogas had no significant impact on η_{el} and operating parameters

Table 3
Proposed MGT models and performance for GSHP model [85].

MGT model	Power [kW]	Heat rate [MJ/kWh]	Efficiency [%]	Exhaust flow [kg/s]	Exhaust gases temperature [°C]	Approx. weight [kg]	Approx. dimensions [m]	Compatible fuel
MGT 01	200	10.9	33	1.3	280	3413	3.8 × 1.7 × 2.5	NG, Biogas, Sour Gas
MGT 02	200	10.9	33	1.3	280	6700	2.5 × 3 × 3.8	Pipeline NG

Table 4
Performance of the ANN and ANFIS integrated with MGT by C.M Bartolini (2010) et al.

Predicted quantity	Range	MAE	RMSE	MRE (%)	R2	Predicting tool
Power output	75–110 kW	0.82 kW	1.074 kW	0.865	1	Levenberg–Marquardt ANN
Fuel mass flow	3.5–7.5 g/s	0.04 g/s	0.066 g/s	0.94	1	Bayesian Regularization ANN
NOx concentration	2–6 ppmv	0.12 ppmv	0.167 ppmv	3.42	0.998	Levenberg–Marquardt ANN
CO concentration	0–425 ppmv	8.27 ppmv	11.94 ppmv	11.98	0.996	Sugeno ANFIS

compared to NG. Led to substantial reduction of CO_2 emissions 19 % at full load. The mean relative error (MRE) used to assess prediction accuracy, assuring developed ANN models performance. With most samples having an error < 1 %. They developed a graphical user interface (GUI) using MS-VB, for a user-friendly architecture in modeling and condition monitoring of MGT's. Industrial application of this system is found in Risaviak, GAS center at Stavanger in Norway and its usage found in many industries across Scandinavia. T. Olsson et al. (2021) [91] used a ML/Data-Driven approach for predictive health monitoring of MGT fleet, improving availability and reducing operating and maintenance costs. They developed constrained linear regression model estimating degradation and a ridge regression model for forecasting degradation based on running hours. Fig. 6(e) display 5000-hour forecasts (black) and negative normalized degradation estimates (blue). Red lines mark points below degradation threshold, system I at around 23,230 h, system III at about 5,367 h, requiring immediate maintenance. Estimation model prediction error, considering known variables, compared with ridge regression forecasting model but using only running hours. Forecasting model appears reliable, matching sometimes surpassing full variable knowledge for several systems (I, II, III, V) (Fig, 07 (f)). Evaluation on five (5) field trials showed good correlation between estimated degradation and power. Main outcomes indicated eliminating need for reference MGT for this system to operate, estimating relative degradation based on initial performance, smooth degradation estimation, easy setting of maintenance thresholds, ability to forecast future degradation aiding dynamic maintenance planning. S. S. Talebi et al. (2022) [92] introduced diagnostic scheme for MGTs, detecting and isolating, operational faults under wide operational load range, considering uncertainties. Scheme utilized MGT off-design model to create training database and employed ANN for fault detection, isolation. In Fig. 7(a), Block "A" represents engine off-design model, providing gas path measurements for clean engine operation. Block "B" represents real measurement values. Deviation of engine measurements (d_m) calculated, fed into trained ANN for fault detection and isolation. Proposed approach (In Fig. 7(b)) demonstrated capability for system-level and component-level diagnostics, considering measurement uncertainties, engine complexity, nonlinearity. This scheme has the potential to improve MGT diagnostics in smart grid applications with uneven load changes harmfully affecting MGT gradual degradation. Further evaluated impact on measurement noise on diagnostics performance. Lower noise improves diagnostics quality but requires costlier sensors, affecting monitoring system expenses. Noise level variations between 0 and 200 % analyzed. In Fig. 7(c) and (d), fault detection success rate remains high (>98 %) at 200 % noise. For fault isolation, noise decreased to 50 % enhances success rate (>99 %) reduces error (<0.2 %). At 200 % noise, fault isolation success rate remains > 90 % with error < 11 %. Noise effects on diagnostics accuracy and cost trade-off are evident.

ANN/ML are increasingly integrating into MGTs, driving future growth. These technologies enhance MGT operations, including emission and load predictions, optimizing performance, reducing environmental impact, and enabling proactive fault detection. They contribute to reliable MGT-based micro-grids, lowering costs, and improving grid stability. Integrating ANN/ML in smart grids facilitates dynamic load management and predictive maintenance planning. Expect exponential growth in ANN/ML-based MGT research, advancing technology for efficient and sustainable energy solutions.

2.5. MGT used in electrical Ground vehicle (EV), Unmanned-Aircraft and marine applications

MGTs have gained popularity as range extenders in hybrid electric vehicles, including UAVs, marine crafts, and underwater vessels, for traction and propulsion applications. MD Arman A. et al. (2020) [93] investigated MGT-based EVs using MATLAB/Simulink, reducing fuel consumption by 2.8 L per 100 km compared to conventional gasoline models. R.M.R.A. Shah et al. (2020)-I [94] explored MTG in Hybrid EVs (HEVs) using power demand strategies (PDS's), focusing New European Drive Cycle (NEDC). A combined mathematical model and experiments conducted selecting MTG. Different PDS evaluated, considering MGT fuel consumption and emissions. MTG had higher fuel consumption than some modern engines, it was suitable for hybrid RE's with intermittent ICE use. MTG emissions met Euro 6c limits for series hybrid EVs. Future work should focus on confirming low particulate matter by MTG exhaust. Although 25-kW MGTs had potential for large executive sedans, further modifications required before they dominate automotive industry. R.M.R.A. Shah et al. (2020)-II [95] found challenges when integrating MGTs to RE-EVs related with ambient temperature and start-stop behaviors, experiments found performance reduction with elevated intake temperatures, suggested intake bay design modifications to mitigate impact. MGT's power fluctuated with ambient temperature, in Fig. 20. MGT produces constant power between −20 and 18 °C, degraded with air property changes. Cold and hot test cycles used to analyze MGT performance, tests carried in two regimes as Cold—test cell temperature below 18 °C and Hot—test cell temperature above 18 °C. These regimes reflected performance of MGT before and after knee value (18 °C), in Fig. 8(a). Tested varying cell temperature (12–24 °C) at maximum power demand (25 kW), shows linear relationship between cell temperature and normalized power output, except for abrupt reductions in temperature, indicating MGT's sensitivity to sudden intake air temperature changes, refer Fig. 8(b).

F. Ji, et al., (2020) [96] numerically and experimentally analyzed recuperated MGT for REEVs, comparing advantages to conventional Diesel-Engine-based RE's (ICE-REs). MGT-RE offered lower emissions and a higher power-to-weight ratio (0.48–0.8 kW/kg). Research involved constructing detailed numerical model for MGT-RE

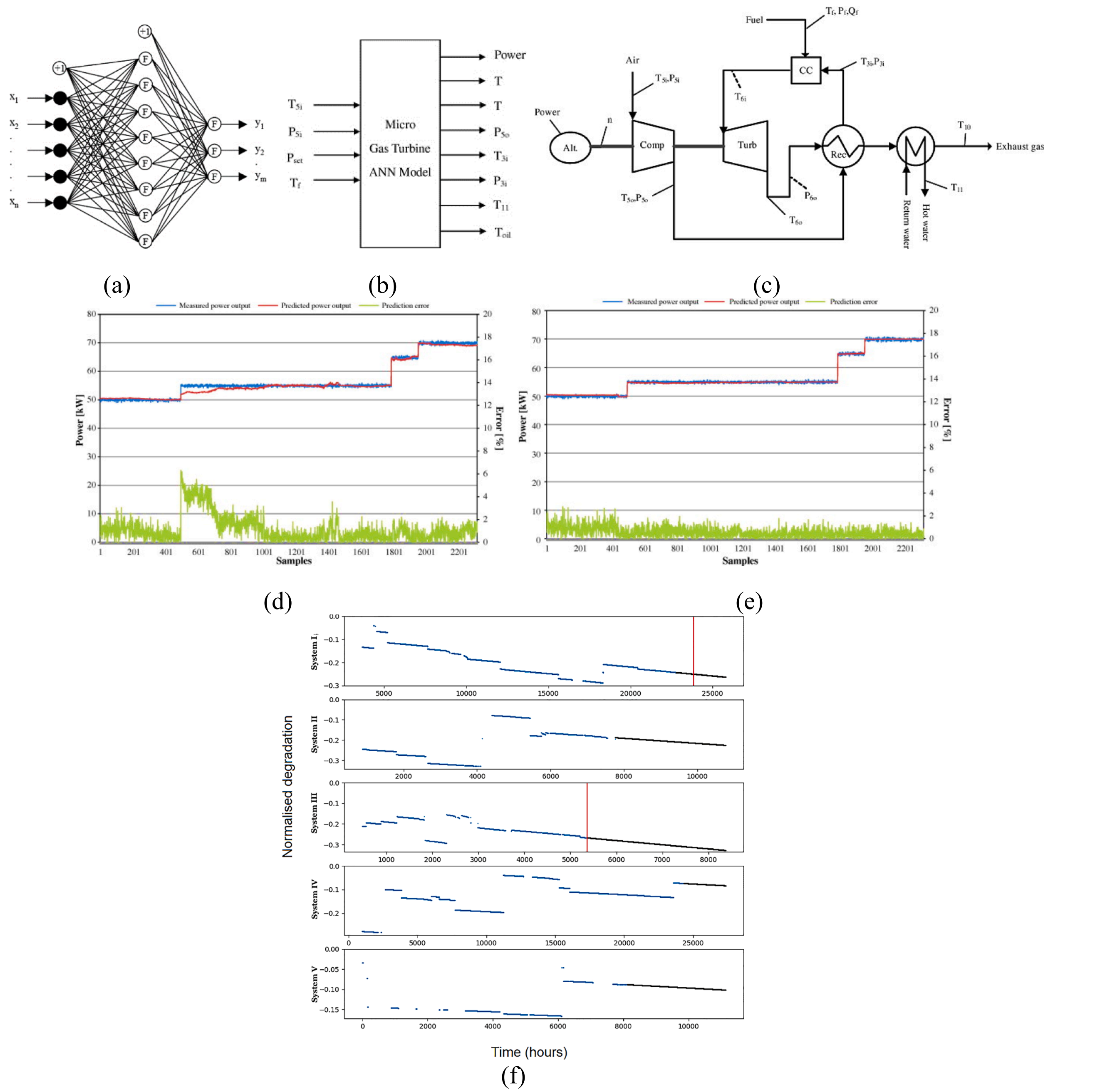


Fig. 6. (I): (a) Schematic of a multi-layer feed forward network, (b) The final model structure and (c) Schematic Measuring points of the Turbec T100, (d) Power output predictions without considering compressor inlet pressure and temperature (e) Power output predictions of final model by H. Nikpy et al. (2013) [89], (f) System forecasts: y-axis provide the normalized degradation, and the x-axis illustrate running hours. The blue curve is estimated degradation from the data, the black curves show 5000 h forecasts. The red lines show when the forecasts are below the threshold, which indicates when maintenance services needed [90]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

simulations later experiments validated results (In Fig. 8(a)), maximum power of 12 kW at 120,000 rpm for TIT 1000 K. η_{th} in regenerative cycle varied with TIT, recuperator effectiveness, pressure ratio and pressure drop. At 288 K, 101.32 kPa pressure, MGT η_{th} in Fig. 8(b). Efficiency increased with higher TIT, recuperator effectiveness, initially with pressure ratio, then declined. Dashed curves (Fig. 8(d)) illustrate MGT efficiency under pressure drops, 1100 K TIT, and 0.5 recuperator effectiveness. Higher pressure drop provided lower MGT efficiency. Study further analyzed REEV performances, driving range, SOC variation, and emissions. NEDC cycle results (Fig. 9) SOC and driving range patterns. SOC a crucial factor for reliable vehicle operations, but SOC decreased with increasing range until 130 km, causing MGT shut down. SOC raised as battery recharge begins until SOC reached 0.7. Fig. 9(I) shows SOC declining at high velocities. Fig. 9(II) illustrates SOC, voltage, and current changes during a single NEDC cycle with MGT shut-off, while Fig. 9(III) shows similar changes with MGT on. Battery discharged positively with decreasing SOC, and during high acceleration, current spikes and voltage drops were significant. Negative current indicated battery charging, increasing SOC. During later NEDC stages, positive current signified discharge, slightly decreasing SOC due to higher acceleration. But the MGT integration caused further uncertainties with design integration and become difficult for dynamic control than ICEs for all terrain modes.

Adeel J., (2021) [97] studied two parameters, battery sizing and

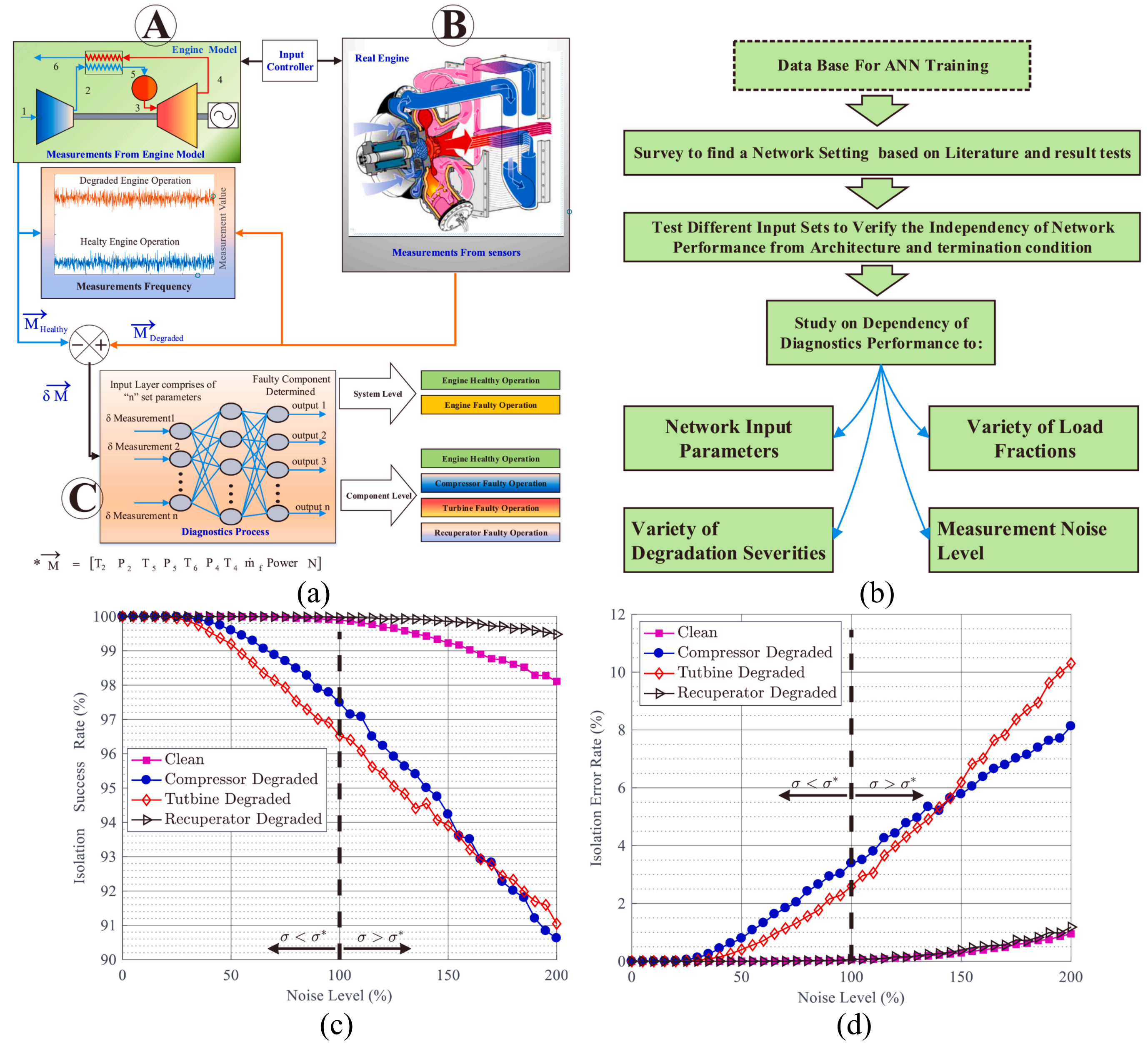


Fig. 7. (a) Block diagram of proposed diagnostic scheme, (b) Steps of preparing and survey on ANN based diagnostics scheme, (c) Effect of Measurements Noise Level on fault isolation success rate and (d) Effect of Measurements Noise Level on fault isolation error rate [92].

charging time, to replace 85kWh battery pack of Tesla Model S P85D with reduced 22-kWh battery coupled MGT of 47 kW shaft power and 32 % η_{el}. Combination reduced weight, charging time during travel stops. MGT's thermodynamic cycle numerically modeled and evaluated using Gas Turbine Simulation Program (GSP). Charging time dropped to 30 min and hybrid range extended. Compressor and turbine isentropic efficiencies of MGT showed greater impact on overall performance. Reduced weight of battery pack (from 540 kg to 130 kg) offered significant cost savings. Heesoo K. et al., (2023) [98] studied conceptual detailed design of MGT-RE with two-spool intercooled, recuperated high-speed MGT, using detailed mechanical design process combining machine theories and numerical methods to improve as a high-efficiency rotor system for 22-kW MGT. Design addressed importance of low-pressure (LP) rotor system, including permanent magnet synchronous generator (PMSG) with round/transversally polarized bar permanent magnet (PM) improving MGT mechanical design and performance. Rotor system supported by dual back-to-back angular contact ball bearings excluded the air-bearing of elevated cost, while the bearing cartridge equipped with squeeze film dampers (SFDs). Several studies included automobile and earth moving machine category where MGTs enrolled complying as prime mover. Volvo tested VT300 GT drive heavy trucks in 2005 had positive progress, Capstone CMT-380 concept car equipped 30-kW MGT achieved total 800 km milage with battery pack, Wrightspeed used recuperated 80-kW MGT for electric trucks, achieved comparable better economic benefits, and Jaguar C-X75 released in 2010 with 4-electric motors driven using 2x-70 kW MGT generators from Bladon Jets. Single MGTs compared to traditional ICE powertrains had power-to-weight ratio of 2 kW/kg. MGT RE-EVs been produced by companies such as Techrules, Mitsubishi, Hybrid Kinetic, and Delta Motorsport [24,93–98]. The MGT-RE offers advantages over conventional REs, particularly higher power-to-weight ratios. As technology matures, number of units manufactured increases, cost of MGT-RE would decrease, making the technology an attractive option for EVs. Advancements in MGT-RE show promise for high-efficiency rotor

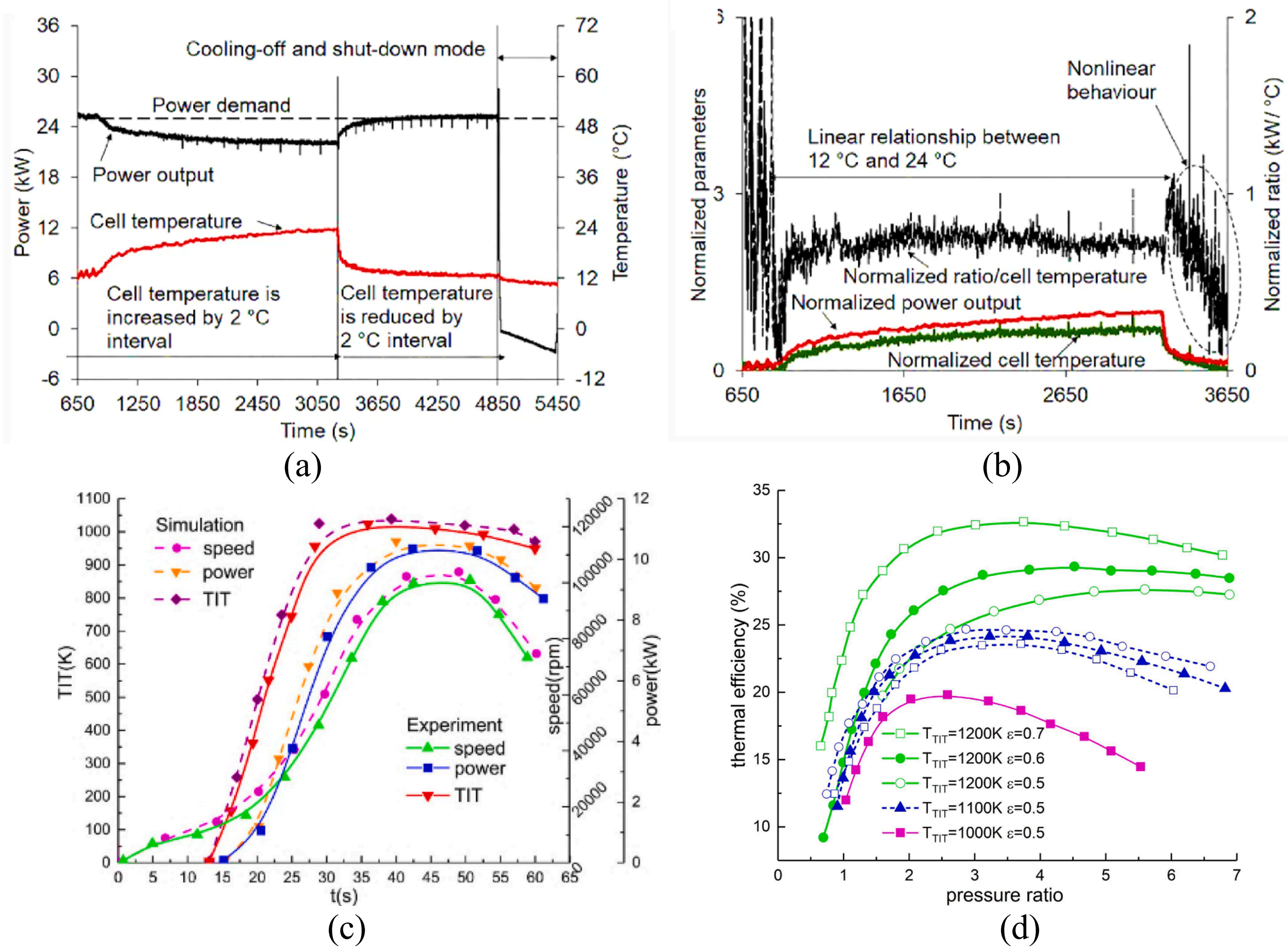


Fig. 8. (a) MGT relationships at cell temperatures between 12 °C and 24 °C at constant power demand and maximum shaft speed a power output vs. cell temperature (b) normalized power output vs. normalized cell temperature [95], (c) Numerical (CFD) and Experimental results comparison of MGT (d) Thermal efficiency of MGT versus pressure ratio [96].

systems with reduced mechanical losses. However, despite benefits, there are major challenges to address, including high initial CAPEX, O&M expenses, potential efficiency losses with varying loads, environmental considerations related to GHGE emissions. Integration to existing EV vehicle platforms even with mono-cage chassis or older ladder frame chassis requiring mechanical design modifications with strength and structural uplifts and specialized maintenance, adding complexity and weight. Furthermore, limited availability of MGT-specific components such as Gas Foil Bearings (GFB), shafting, and engine mounts could pose supply chain challenges, as well as difficulties in overhaul and repairs in the event of a vehicle breakdown due to the lack of readily available spare parts compared to ICE or battery-powered vehicles. Overcoming these downsides will be crucial for widespread adoption. However, competing against already matured technologies, such as battery or fuel cell-powered traction and propulsion systems, will present challenges. MGT-based research activities on EVs show less progress in the future. Nevertheless, integrating MGTs into Unmanned Aerial Vehicles (UAVs) or underwater vehicles (UUVs) provide steady growth considering MGTs as prime mover or APU for electrical propulsion and on-board power generation systems.

2.6. MGT: Combustion kinetics and combustion chamber

Many researchers have considered the Combustion Chamber (CC) and Combustion process of MGT as important aspect in assessing performance. However, this area of study is highly uncertain and limited, with many assumptions. Research deal with complex flow behaviors, fluid, and thermal analysis with un-identified but highly theoretical turbulence characteristics [99–101].

However, Hsin-Yi S. et al. (2014) [102] experimented to understand combustion performance of H_2/CH_4 blended fuels with innovative 'Can type' MGT combustor. CFD simulations conducted, varying H_2 content mixture of blended fuels (0 %–90 %). Fig. 10(a) and (b) illustrate the CAD model of Can Combustor. Mixed amounts of CH_4 with H_2 improved combustion efficiency by increasing flame temperature. Higher H_2 (%) decreased fuel flow rate and heat input, making power shortages. To make up power loss, comparisons made with constant fuel flow rate or heat input. Fig. 11(b) as trend, H_2 replaces CH_4, led decreased fuel flow and heat input with higher H_2 accumulation. Important flame temperature parameters $T_{pz,\ avg}$ and $T_{4,\ avg}$ analyzed in Fig. 10(c). With 10 % H_2 substitution significantly raises average flame temperature in primary zone compared to CH_4. Flame temperatures stayed relatively steady with moderate H_2 substitution, peaking at certain percentages. High reactivity of H_2 increased flame temperature rapidly, but excessive substitution reduced high-temperature regions, risking power loss. Turbine-related parameters; $T_{4,avg}$ and pattern factors are crucial for stable combustor operation. While exit temperature increased with H_2 substitution, pattern factor decreased. Fig. 10(d) higher H_2 % increased flame and exit temperatures with enhanced heat input, although pattern factor remained stable, indicating manageable temperature fluctuations, benefiting MGT performance, caused cooling and NO_x emission issues. Research primarily explored how H_2 substitution impacts MGT

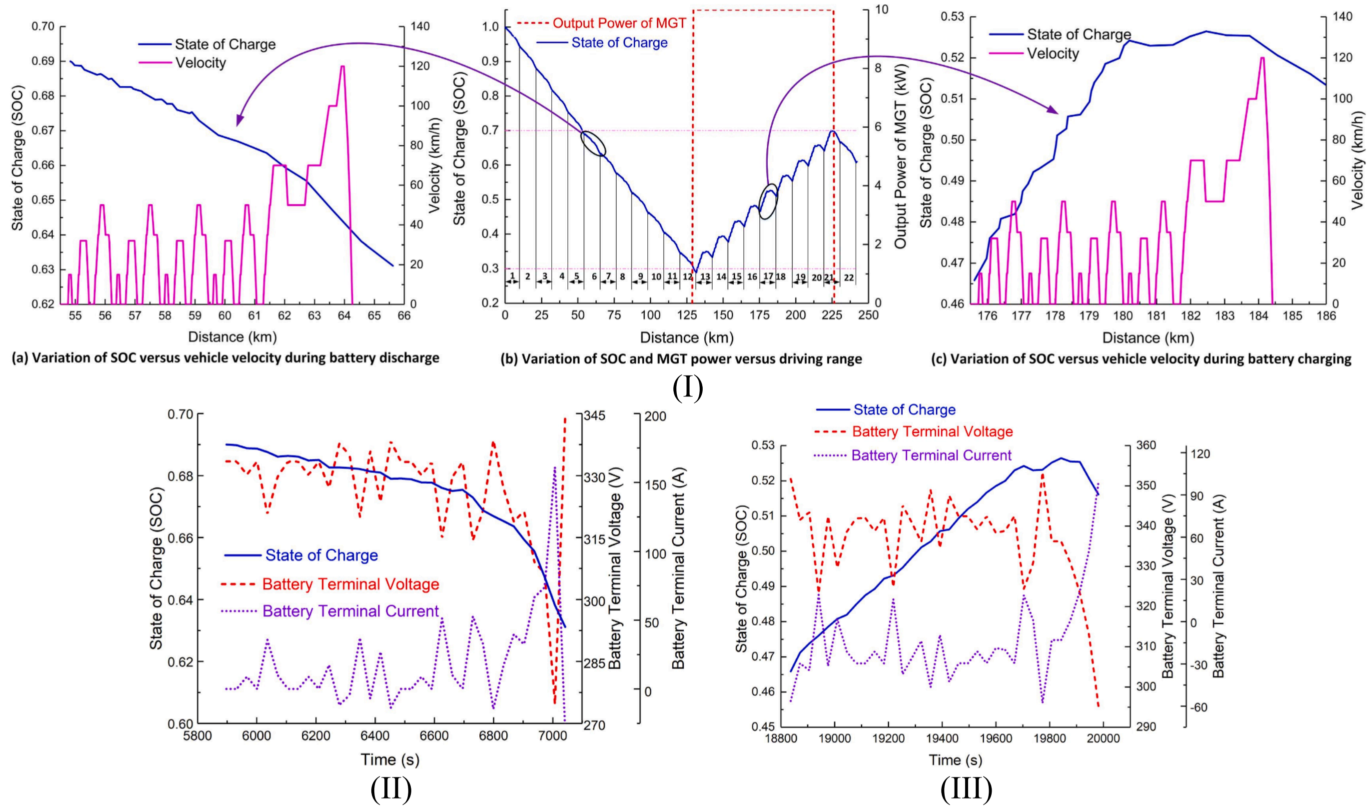


Fig. 9. (I) Variation of SOC and MGT power versus driving range (II) Variation of battery parameters during a single NEDC when the MGT is switched-off and (III) when the MGT is switched-on [96].

combustion under constant fuel injection velocity. This opens 2-scenarios, H_2 addition at fixed fuel flow rate, H_2 addition at constant heat input. With constant heat input, higher H_2 % led to wider, shorter flames, sustaining MGT power, with expense of increased CO emissions and reduced combustion efficiency. Design modifications for the combustor, particularly fuel injection and cooling strategies, can be suggested to address these challenges.

M. Cristina Cameretti et al. (2016) [103] conducted numerical investigation on MGT combustors using different fuels, including conventional NG, biomass gasification fuels, solid waste pyrolysis. Utilized 2D axisymmetric CFD simulations using ANSYS FLUENT®. For low-calorific-value fuels, combustor operated under off-design conditions, caused variations in temperature distribution, flame propagation patterns, pollutant formation. To increase combustion efficiency with LHV fuels by increasing fuel injection through pilot line. Fig. 11(a) 10 % of fuel flow directed to pilot line, this was tripled (3x) (referred to as "*_3PIL*") improved reaction speed. The approach yielded increased progress variable for both fuels, though the flame speed rise was less pronounced, potentially due to increased inert content in main combustor. Despite this factor, "*_3PIL*" chosen for biogas from anaerobic digestion due to its positive impact. In Fig. 11(b), increasing pilot injector fuel flow raised temperatures in main region and expands zones supporting reaction progress. Modified pilot location-controlled NOx formation, shifted temperature peaks to higher-inert content region, achieved smoother temperature profiles in secondary/dilution zones. This adjustment partially indicated a flameless regime, reducing flame extent, retaining some presence. Increasing pilot injection rate reduced unburned fuel & 15 % CO emissions, modifying pilot location decreased 50 % NO emissions. Ibrahim I. E. et al. (2017) [104] proposed CFD based CC for microturbine, best chamber geometry had flame holder diameter (d) of 50 mm, chamber height (h) of 60 cm, and 4 holes with varying sizes (6, 8, and 10 mm) with a dead zone between combustion zone and dilution zone. Dimensions considered as non-dimensional parameters for future studies adaptability. Experimental testing using LPG fuel showed stable combustion with CO emissions < 100 ppm and TIT below 900 °C. Proposed CFD methodology was accurate, good prediction of flame distribution, but slightly overestimated temperature, CO emissions and underestimated NOx emissions compared with experiments. Table 5 provides CFD and Experimental results, a slight overestimation of temperature and CO emission values, while lower values predicted for NO_x emissions compared with experimental results.

Alessandro Bo et al. (2017) [105] analyzed a commercial MGT-CC for fuel flexibility using CFD. They investigated performance of Turbec T100-P MGT, with transition from NG to a H_2-rich syngas. Significant changes in temperature, flame front shape, combustor outlet temperature, and NOx emissions observed during fuel transfer. NO_x emissions were below 8 ppmvd at 15 % O_2 during transition and low as 2 ppmvd at 15 % O_2 with pure syngas. Combustion regime shifted between well-stirred reactor and thin reaction zone with partial flame quenching when burning CH_4 alone. Maaz Ajvad et al. (2020) [106] numerically studied effects of combustor with "casing rotation" with fuel as H_2/CO syngas. Casing rotation around main axis (shaft) caused flame shifting and stabilizing along the wall, leading to increased pattern factor and exit temperature. Power shortage with syngas fuel resolved by increasing fuel flow rate but resulted severe temperature fluctuations. Seliger-Ost (2021) [107] experimentally studied biogas mixture combustion characteristics (varying CH_4 and CO_2 content) with NG in 6-nozzle combustor based on FLOX® which is integrated to 3-kW MGT. With FLOX concept, fuel injected coaxially into a high momentum air flow using fuel nozzle. This design allows well-controlled, efficient combustion, ensuring thorough mixing of fuel/air. High momentum jets, dilution by flue gas contributed stable combustion and low emissions. Adjusting air split to leaner conditions further reduced combustion temperature and NO_x emissions. This study marks the world's first successful operation of single-staged FLOX-based combustor in an MGT. I.I. Enagi et al. (2022) [108] experimentally researched new CC

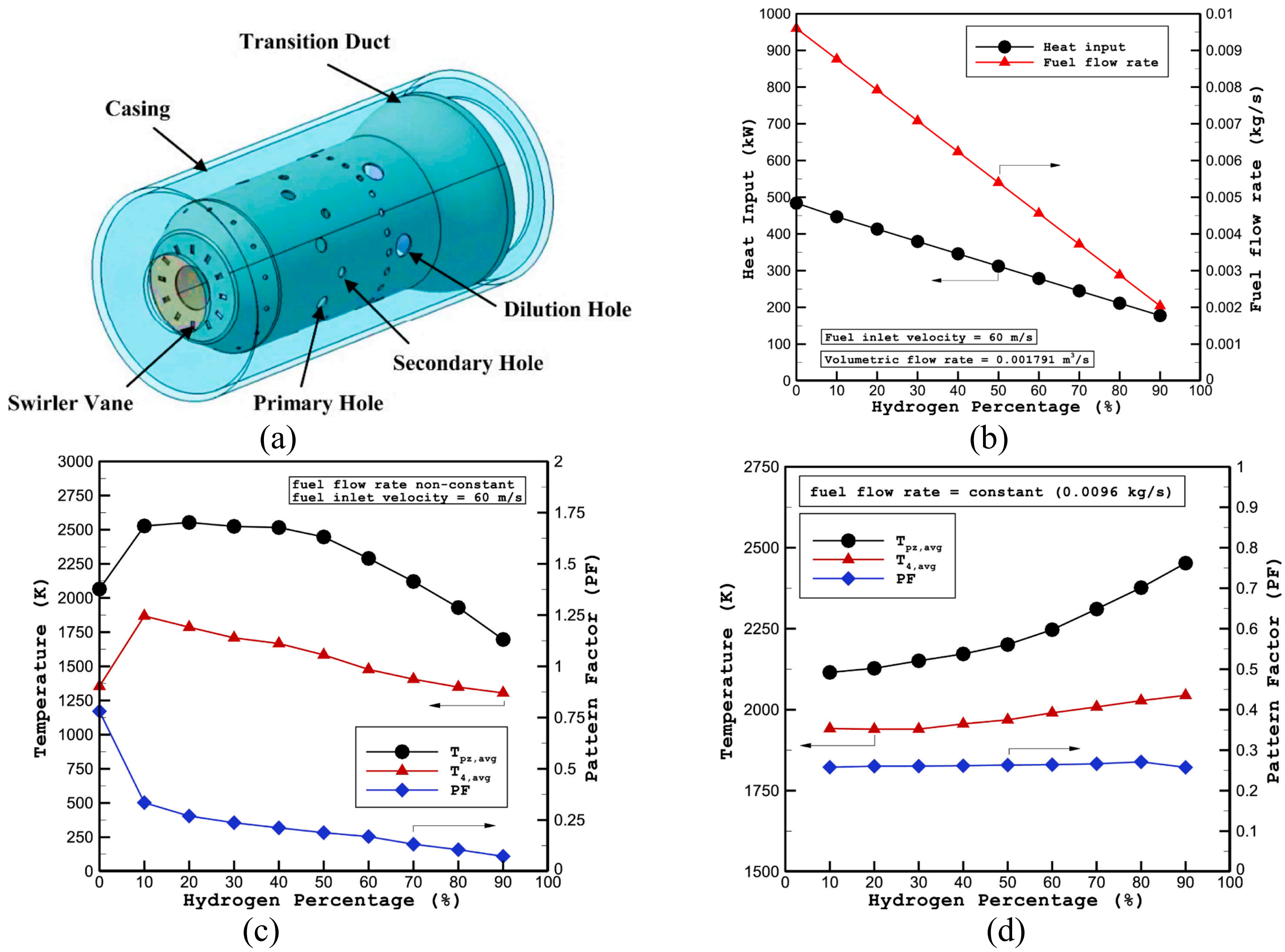


Fig. 10. (a) 2-D layout of innovative MGT, CAD model Can Combustor (b) Variations of fuel flow rate and heat input with H_2 substitution % of blended fuels (fuel injection velocity = 60 m/s, volumetric flow rate = 0.001791 m^3/s). Variations of average flame temperature in primary zone, exit temperature of combustor and pattern factor (c) with H_2 % (d) with H_2 % at fixed fuel flow rate [102].

geometry optimized for liquid biofuels (Bio-Diesel) for MGTs. They compared spray characteristics of "palm biodiesel" with conventional diesel fuel using cold-flow fuel atomization test rig. Experiments performed using single-stage MGT and twin-stage MGT on CHP mode. Diesel fuel provided higher TIT and turbine power with HHV compared to biodiesel. Palm biodiesel exhibited lower CO emissions; leaner combustion conditions resulted higher NOx emissions compared to diesel. Twin-stage MGT-CHP, palm biodiesel compensated for its LHV bringing increased air flow rates, achieving similar electrical and power outputs compared to diesel. Overall system efficiency mainly governed by HRU (Heat Recovery Unit) efficiency; palm biodiesel achieved higher overall system efficiency compared to diesel. Experiments suggested palm biodiesel can be effectively used as 100 % operational fuel for MGT providing same performance of diesel with power output, fuel consumption and lower emissions. Yize Liu et al. (2022) [109] proposed multi-fidelity approach Fig. 12 illustrate general workflow. For efficient micro-combustor design, integrating preliminary design models, high-fidelity modeling, experimental testing, and refinements are grouped together. They conducted case study on MGT producing 12kW_{el} and 200 kW_{th} using swirl-stabilized, multi-point injection type combustor. Primary design involved defining design parameters, combustion chamber layout, flow distributions, and burner geometries. High-fidelity modeling using ANSYS Fluent v19.1 with k-ε turbulence model and flamelet-generated manifold approach defined system model analyzing turbulence flow, mixing, combustion, and emissions physics. Performance criteria for optimal combustor geometry defined, and the modeling approach was validated by comparing simulation results with experimental data. Results showed lower NOx emissions for biogas but flame stabilization issues due to lower CH_4 content, which solved by modifying the swirler blade angle and adjusting the primary mixing hole axial location.

In the high-fidelity modeling process (outer green boxed section) shown in Fig. 12, several design factors that were partially modeled in preliminary stage, such as chamber dimension, dome front configuration, fuel nozzle orifice number, dilution hole arrangement, were investigated in detail. Performance criteria for optimal combustor geometry pre-defined, including combustion stability, low pressure loss, desired flow pattern, desired flame shape, reduced emissions with %'s, and accepted outlet temperature distribution factor. Modeling approach validated by comparing LES results and measured experimental data. High-fidelity modeling data useful in refining and finetuning low-order models at initial preliminary design stage, this creates repeated and iterative-looping process for improved MGT combustor designs. Further numerical analysis studied 12 kW MGT assessing usability of biogas for emission and performance, indicating lower NOx emissions but flame stabilization had issues with lower CH_4 %. A stabilized flame front gained through modifications in swirler blade angle and adjusting primary mixing hole axial location. Pappa A. et al. (2022) [110] conducted detailed comparison by LES in NG combustion. Used Turbec T100 MGT with different diluted conditions (Water and/or CO_2), resulted in wider

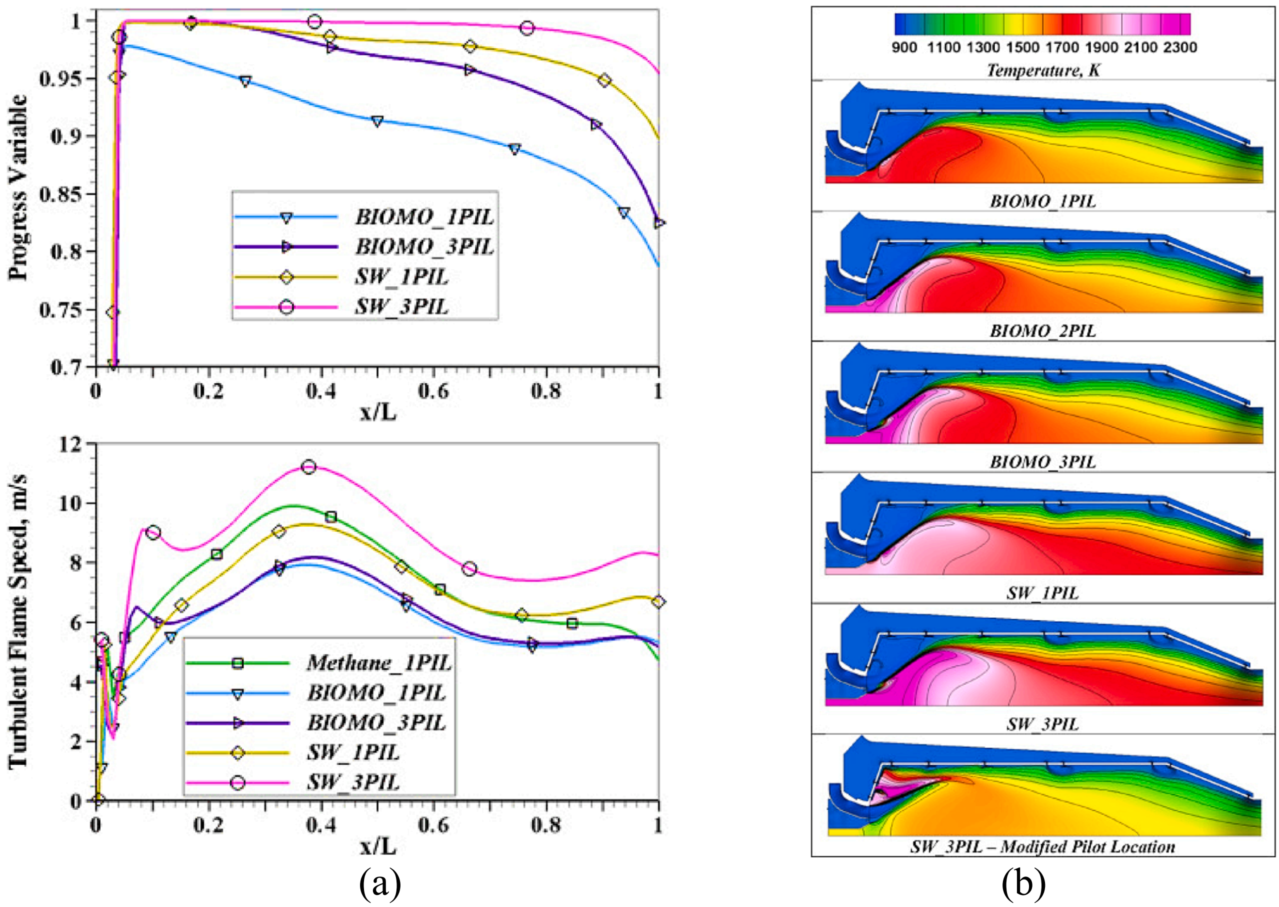


Fig. 11. (a) The effect of the increased fuel pilot rate on the progress variable and the turbulent flame speed and (b) Temperature distributions for different pilot injectionsMGT Cmobuster [103].

Table 5
Comparison between experimental and CFD simulation results [104].

Parameters	Experiment	Simulation	Error (%)
Fuel composition (vol%)	70 % butane and 29.5 % propane	70 % butane and 30 % propane	–
Air inlet pressure (barg)	0.7	0.7	–
Air flow rate (kg/s)	0.07	0.07	–
Excess air (%)	37	37	–
TIT (°C)	920–960	1069	16.2–11.4
CO (ppm)	50–60	69	20–15
NOx(ppm)	34–20	4	88.2–80

reaction zone and reduced outlet temperatures. Research in MGT combustion kinetics and CC applications aims to improve MGT performance and efficiency. Includes enhancing fuel flexibility, optimizing combustor designs, and blending different fuels. Improved CFD simulations and methodologies are instrumental in understanding impact of fuel mixtures, combustion chamber geometries, swirl-stabilized configurations. Notably, research is progressing towards improving mixing patterns, enhancing combustion efficiency, and reducing emissions. However, challenges remain, particularly regarding stability of low-calorific-value fuels and addressing NOx emissions with H_2-rich syngas. Continued research efforts should focus on these challenges and optimizing combustor geometries ensuring stable operation and reduced emissions across a wide range of fuel applications. For micro-combustors in confined spaces, further studies are needed to compare combustion intensity (kW/m^3 atm) and investigate Rayleigh flow and Fanno flow effects on their performance. Overall, advancements in MGT-based combustion kinetics and CC-related research show promise for enhancing efficiency and environmental performance soon. Research in this field is also moving towards exploring scaled-down versions of rotating detonation combustion (RDC) and oblique wave detonation combustion (OWDC) concepts, aiming to replace conventional MGT combustion methods. These concepts represent promising options for future combustion related MGT studies.

2.7. MGT: Radial type compressor and turbine based research

Turbine and compressor define two most important components linked together in MGTs. Some designs involved shaft linkage with rotational speed (rpm), and several new developments removed physical linkage but connected with aerodynamic similitude of speeds between the compressor and turbine. However, both categories subjected to torsional vibrations [111,112].

Donghyun Lee et al. (2016) [114] assessed reliability of Gas Foil Bearings (GFBs) in hot section of MGT using numerical analysis with secondary direct air flow passage for cooling. Analysis accurately predicted plenum and bearing sleeve temperatures, showing 5–20 °C reduction in sleeve temperature when cooling air directly injected from mainstream, compared to injection through reservoirs. This advancement future will improve GFB cooling and most likely improve MGT performance around 5 %. Jun Su Park et al. (2013) [113] examined heat transfer and temperature distribution MGT. (Fig. 13(a)) different thermal insulation materials, varying thermal conductivity (0.1 to 100). Local temperature data with materials such as Inconel 601 and Zirconia cases compared in Fig. 13(b). Inconel 601 case, conduction heat transfer

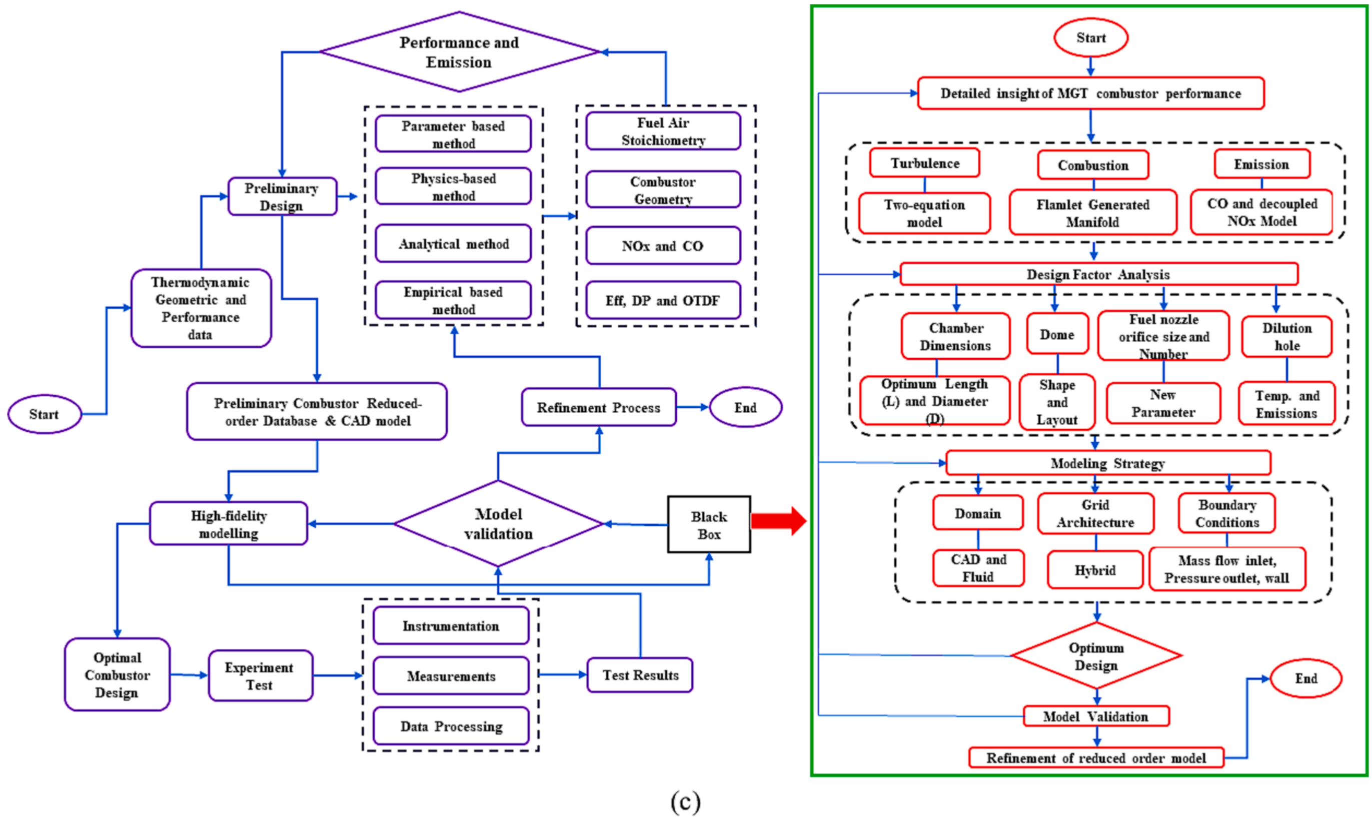


Fig. 12. General overview of framework for micro combustor design, modeling, testing and validation and combining High-fidelity novel modelling methodology for MGT combustor [109].

increases, leading to elevated temperatures inside casing and compressor impeller. Compressor-driven incoming flow benefits heat dissipation from generator, making its temperature similar in both cases. Fig. 13(c) Illustrates temperature profiles along rotational axis with different thermal insulation conductivities. Higher conductivity led to elevated temperatures near insulation wall, convective heat transfer rapidly reduces temperature. Generator temperature remained unaffected by insulation conductivity. Choice of insulation material and its properties showed greater impact on heat distribution inside MGT enclosure. H. Cheng et al. (2023) [116] studied impact of rotor wall cooling on transonic MGT compressor. Miniature 1.5-stage axial compressor having 36 blades operated at 250,000 rpm. Optimal wall cooling improved η_{comp} by 3.7 %, increased P_r by 1.8 %. Cooling effect delayed laminar separation transition, reduced separation losses, and enhanced flow reattachment. In Fig. 13(d) and (e) axial shear stress on rotor's dimensionless surface to investigate wall cooling's impact on 2D flow separation. Axial wall shear components identify laminar separation, transition onset, and turbulent reattachment locations. Laminar separation begins where skin friction shifted from positive to negative, while turbulent reattachment marks shift from negative to positive. The laminar separation bubble (LSB) length is the distance between these points. Without cooling, laminar separation starts at 17 % chord position, reattaching at 45 %. Under cooling, laminar separation started closer to blade trailing edge, while turbulent separation was delayed. At TR = 0.6, LSB is minimal (15 % C position), but wall shear stress slightly increased, constraining further middle blade improvement. Cooled walls affected blade tip and 50 % span similarly restraining LSB and turbulent separation. Wall cooling decreases shear at about 60 % C (TR = 0.6), potentially enhancing aerodynamics near blade tip. Transition onset, marked by negative skin friction surge, delays with cooling, shortening LSB length. It also improved the matching relationship between the rotor and stator, further reducing flow separation losses. However, additional thermal and viscous dissipation, limited continuous aerodynamic performance increase. Specially with micro scale compressors, fraction of efficiency improvements produces 10–20 % overall efficiency improvements. M.J. Kim et al. (2017) [115] focused the impact of internal leakages on performance of 30 kW MGT. Identified 03 types of leakages (Referring to original article [115]; Fig. 8). Leakage 1 and Leakage 2, each with a 1 % leakage rate, resulted modest power fluctuations and efficiency decreases. Leakage 3 had substantial negative impact, causing significant reduction in power and efficiency. Its effects were like those associated with compressor fouling and turbine erosion. To differentiate between these types of leakages and other factors, the study used sensitivity ratios of fuel flow rate to pressure ratio, which allowed for distinguishing Leakage 3 from fouling and erosion. Erosion, although showing similar pressure ratio trends, had smaller fuel sensitivity ratio compared to Leakage 3. Study emphasized importance of understanding leakages in effectively diagnosing, addressing performance in MGTs. Research findings supported by detailed analyses, referring to original article [115]; Fig. 13, which further highlighted varying effects of internal leakages on MGT performance. Despite these advancements, future research requires to address factors like blade solidity, temperature ratios, optimal cooling distribution for different MGT compressor and turbine blade geometries to further enhance technology's efficiency and reliability. Still MGTs lack turbine "blade cooling" deployed. Newest advancements and trends suggest continuous efforts in optimizing designs and cooling methods will play a significant role in shaping the future of MGT-based radial type compressor and turbine applications. However, future research activity growth in this branch of MGT-based research work be stagnated or slower and hold less potential. The trend towards a counter-rotating axial compressor system would highly unlikely be adopted for MGT-based research in the future. Since much of the design and development activities were carried out in past two decades, would require breakthrough in radial compressors and

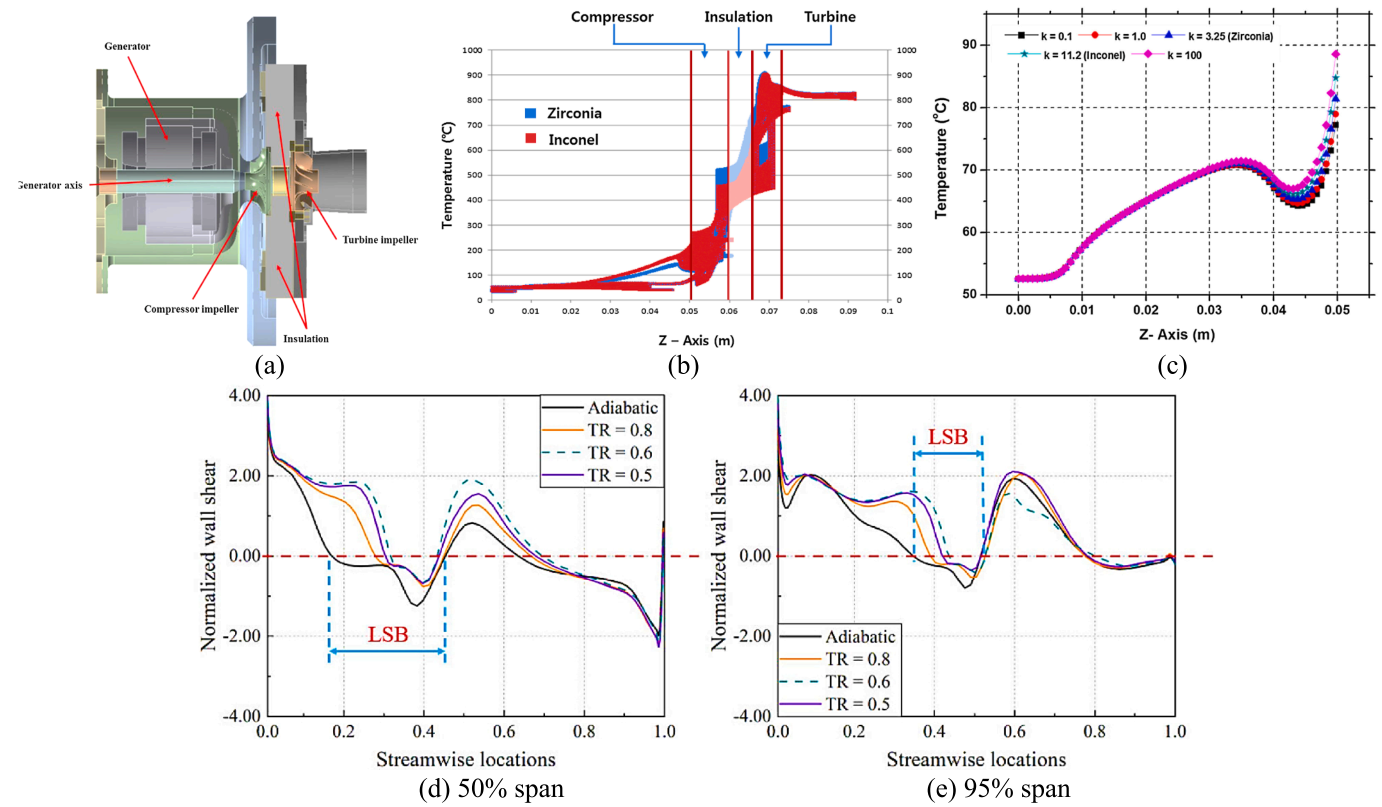


Fig. 13. (a) Layout of MGT and generator, (b) Local temperature comparing with the Inconel case and the Zirconia case, (c) Local temperature on the center line of rotating axis in the various thermal conductivities; Generator and compressor. [113], Fig. 33: Skin normalized wall shear of the rotor suction side at different spans. [116].

turbine-related activities to gain substantial growth in MGT-based research activities to progress in future, especially with relatively smaller market share of MGTs.

2.8. MGT: Recuperator

Recuperators boost MGT efficiency by preheating compressed air with exhaust gas heat, improving fuel efficiency. Cost-effective, high-efficiency designs for small MGTs have been developed, ensuring effective operation while managing costs and weight. Maintaining high effectiveness and low-pressure loss is vital for MGT recuperators, with micro designs now available for MGTs under 500 kW. Stevens et al. (2006) presented general design requirements, suggesting pressure drops on cold side of recuperator to achieve high heat exchanger effectiveness and maximize cycle efficiency. T. Liu et al. (2018) [117], demonstrated correlation between cold and hot side pressure drops in micro recuperators for MGT, achieving close to 1 % accuracy in cycle efficiency improvement with optimized design for 1.5 kW MGT. Also [118,119] studies highlights Swiss-Roll Recuperator (SRR) with thermal design and model analysis, finding shows increasing number of turns in SRR improves effectiveness but leads to higher pressure loss. S.M. Hosseinimaab et al., (2021) [120] analyzed recuperator design and performance for < 1 kW applications using CFD, identifying optimal pipe diameter combinations and inner pipe diameter range.

K.H. Do et al. (2016) [121] investigated recuperator design with offset strip fins (Fig. 34-(I)) to suit MGTs at elevated temperatures. This unit prototyped for experiment, and Fig. 14 (I) and (II) (a)/ (b) illustrates specially designed and fabricated recuperator unit consisting of several layers of materials and layers. Experiments varied hot air stream's mass flow rate (1.5—4 g/s) and inlet temperature (250—500 °C). Total pressure drops at elevated temperatures. Accurate pressure drop required measuring the inlet pressure of each air stream. The recuperator's effectiveness remained constant regardless of warm air stream's inlet temperature, indicating minimal impact on effectiveness from fluid mean temperature variations. Researchers implemented modified analytical model which accurately predicted pressure drop, heat transfer, and effectiveness of offset strip finned recuperator. Fig. 14-(IV) presents a comparison between experimental and model-predicted effectiveness results. The dashed black lines represent the effectiveness from a simple model using empirical factor correlation, while the solid red lines represent modified model results. Modified model applies j correlation [18] in the core region and correlation in outlet region of recuperator. Fig. 14(IV) (a) and (b) shows that the simple model significantly overestimates effectiveness concerning hot air inlet temperature and mass flow rate, whereas modified model exhibited excellent agreement with tested results within a maximum 2.2 % error. Suggests that predictions from the simple model might overly boost MGT thermal efficiency due to its impact on recuperator effectiveness and pressure drop. It reflects, proposed modified model successfully predicts pressure drop and heat transfer characteristics of offset strip fin recuperator for MGTs as well as increasing the overall thermal efficiency.

T. Kim et al. (2019) [122] investigated wavy fin recuperator for an MGT with < 1 kW power. Recuperator was fabricated using laser welding (Fig. 15(I)). Hot air inlet temperature ranged from 250 °C to 500 °C, and mass flow rate varied from 1.5 g/s to 4.0 g/s. Effectiveness increased to 67 % with a higher inlet temperature. However, increased mass flow rate at 500 °C, effectiveness decreased to 59 %. Similar to [121] an analytical model was developed, which accurately predicted pressure drop and heat transfer, showing good agreement with experimental results (relative errors < 5.0 % for effectiveness and 11.5 % for total pressure drop). Further studies can be suggested to optimize heat transfer surface configurations through empirical correlations and 3D simulations. When compared analytical model with experimental data

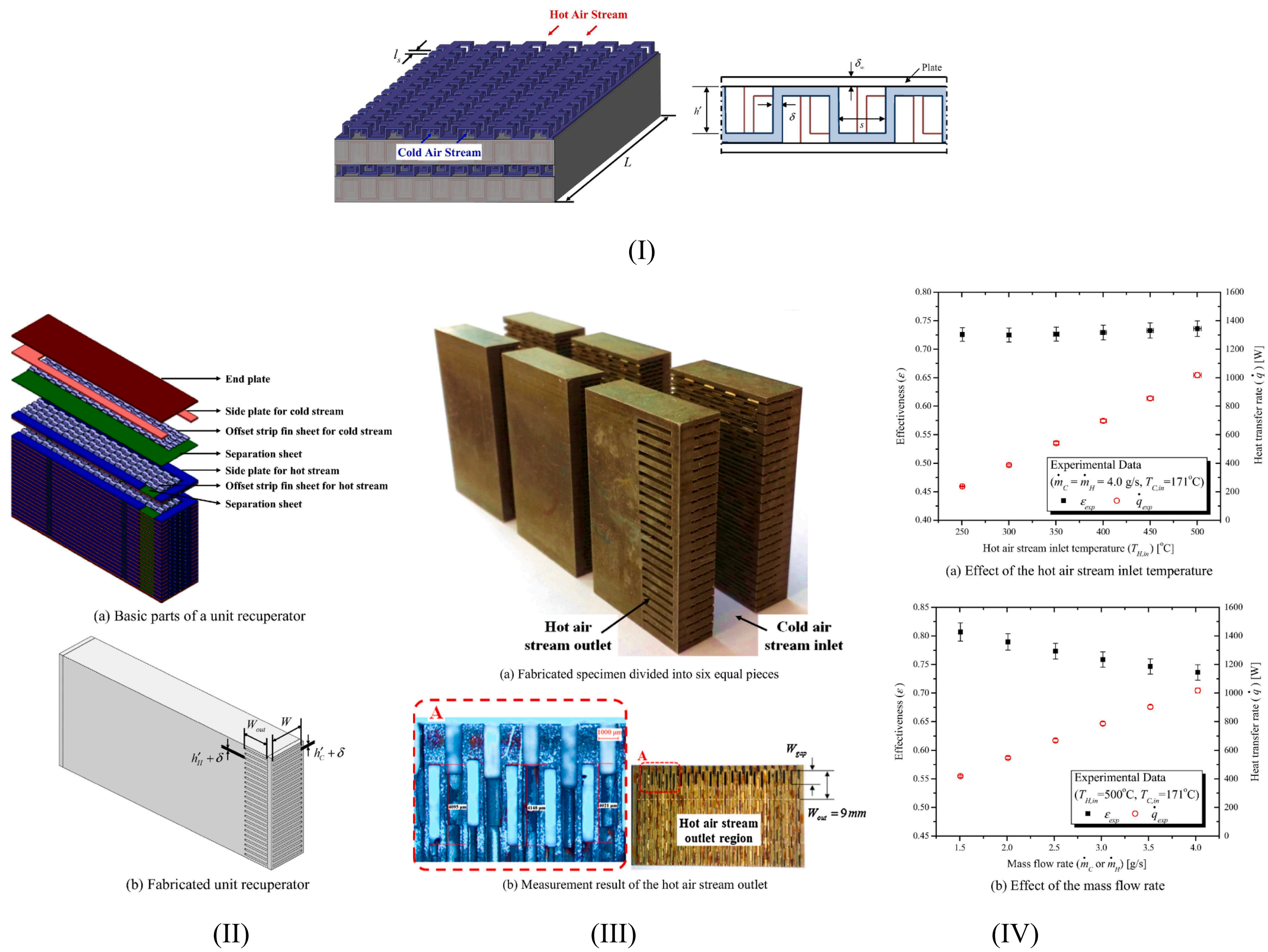


Fig. 14. (I) Offset strip fins-based recuperator, (II) Schematic diagram of a unit recuperator with offset strip fins, (III) Real images of the unit recuperator, and (IV) Comparison of the experimental and model prediction results of the effectiveness. [121].

for wavy fin recuperator's cold and hot air streams. Two model versions must be considered, one including all regions (inlet, outlet, and core), and another focusing only on core area. Results in Fig. 15. II (a) and (b) showed excellent agreement, with maximum 5.0 % error for effectiveness and slight variations for outlet temperatures. Even the core-focused model aligned well, however slightly lower due to negligible heat transfer in certain regions. This model (based on the analyzed results) successfully assesses high-temperature performance by considering the core area. Applicability spans 1.5–4.0 g/s mass flow rates and 250–500 °C hot air inlet temperatures. In Fig. 15. (III), results express total pressure drop by comparing experimental data with an inhouse coded numerical predictive model. Fig. 15. III (a) considered cold air at 171 °C and 4.0 g/s. Model results closely aligned with experimental data, showing a maximum error of 2.1 % for cold air and 9.7 % for hot air. However, excluding pressure drop caused by a sharp bend in outlet region underestimates experimental results up to 31.4 % regardless of hot air temperature. This bend contributed 9.1 % and 26.4 % of pressure drop for cold and hot air sections. Fig. 15. III (b) shows mass flow rates at 500 °C hot air and 171 °C cold air. Model's maximum 11.5 % relative error accurately predicted total pressure drop. When pressure loss from the sharp bend and inlet frictional drop was disregarded, this model deviated from experimental data. Highlights the importance of this data when including pressure losses near inlet and outlet regions (Regions I and III) for an accurate total pressure drop prediction in wavy fin recuperators. A review on MGT recuperators by G. Xiao et al. (2017) [123] reported several design types of heat exchangers improved by renowned manufacturers. RSAB developed a completely welded primary-surface recuperator shown in Fig. 16(a) [124], with a counter-flow heat exchanger configuration and stainless-steel plate matrix sealed by laser welds. Ferrari et al. [125,126] investigated T100 recuperator (like RSAB's) under steady-state and part-load conditions, contributing to design improvements and theoretical model validation. Honeywell Corporation developed primary-surface counter-flow recuperator in Fig. 16(b) [127], with welded CC plates at main heat transfer region. Wilson et al. designed plate type micro-channel recuperator based on silicon carbide (SiC) in Fig. 16(c) [128], achieving an overall electrical efficiency improvement from 27 % to over 40 %. Capstone Turbine Corporation began commercial production of recuperated MGT with annular and fully welded primary-surface recuperators, offering benefits of minimal ducting, simplicity, and compactness in Fig. 16(d) [129]. ACTE developed a spiral recuperator for MGT applications in Fig. 16(e) [130], with an all-welded structure comprising a pair of corrugated sheets forming two spiral-shaped chambers and air feed manifolds. Rolls-Royce developed a spiral recuperator in Fig. 16(f), with gas entering from bottom and air from top, achieving a high heat transfer coefficient and low pressure drop [123]. Swiss-Roll's recuperator showed in Fig. 16(g) [130] composed of two flat plates wrapped around each other, creating two concentric channels of a rectangular cross-section.

Primary-surface recuperators are the most popular type due to their

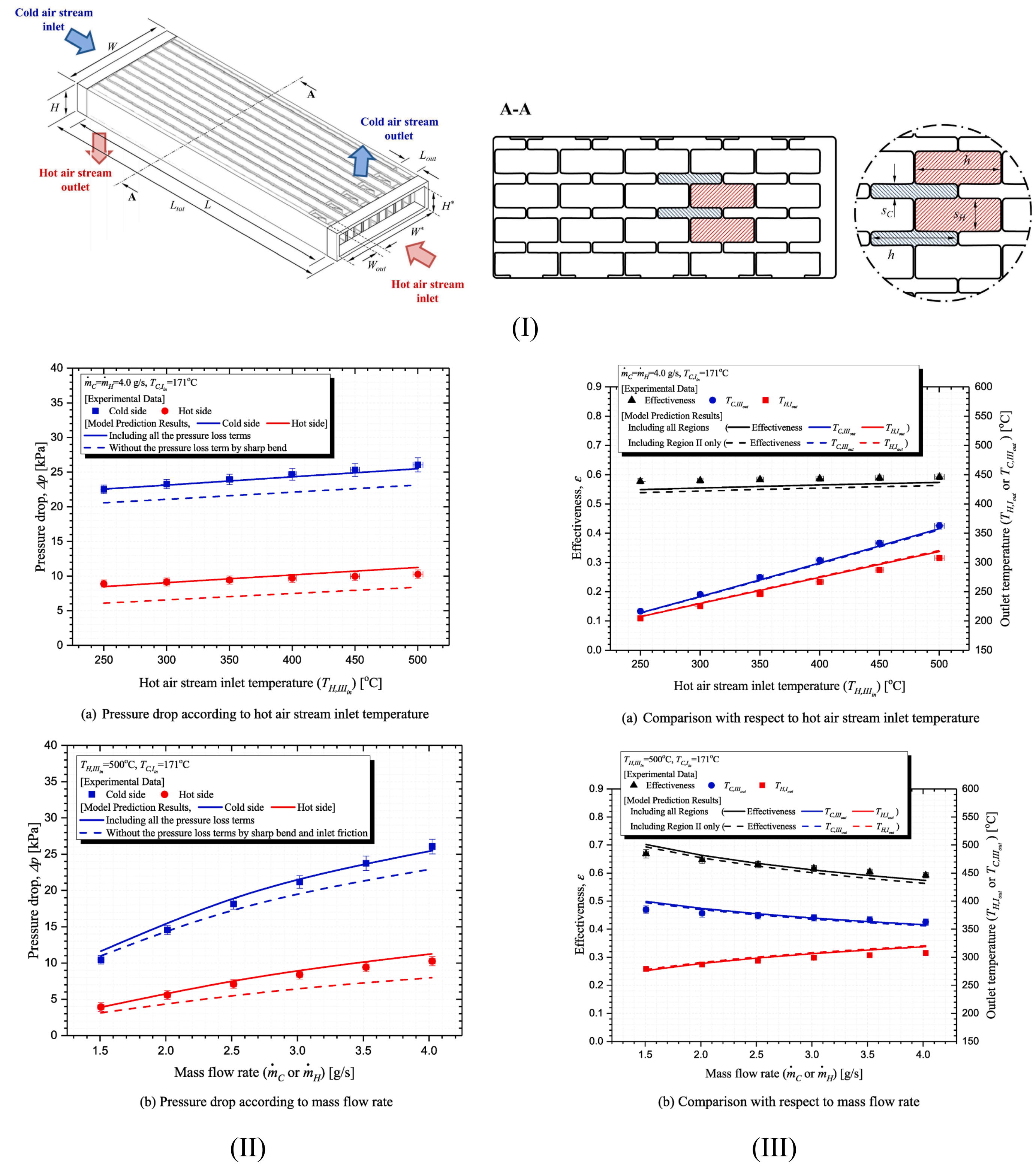


Fig. 15. (I) Cross-sectional view of wave fin recuperator, (II) Comparisons of total pressure drop, (III) Model prediction results for effectiveness and outlet temperatures. [122].

compactness and effectiveness. Further research is needed on pressure drop and heat transfer effectiveness, as well as configuration of heat transfer surfaces, to achieve high performance with stability of MGT operation without thermal efficiency fluctuations in the thermodynamic cycle. Optimization methods need to consider complex relationships between pressure loss, heat transfer effectiveness, compactness, and cost. In such cases, multi-objective optimization (MOOP) methods such as GA, MOGA, and PSO techniques seems attractive. These consider minimizing entropy generation, field synergy principles (leveraging the interactions between different fields or flows), entransy (ability of an object to transfer heat similarly as electrical energy describes the ability of a capacitor to transfer charge) dissipation theory, and constructal law

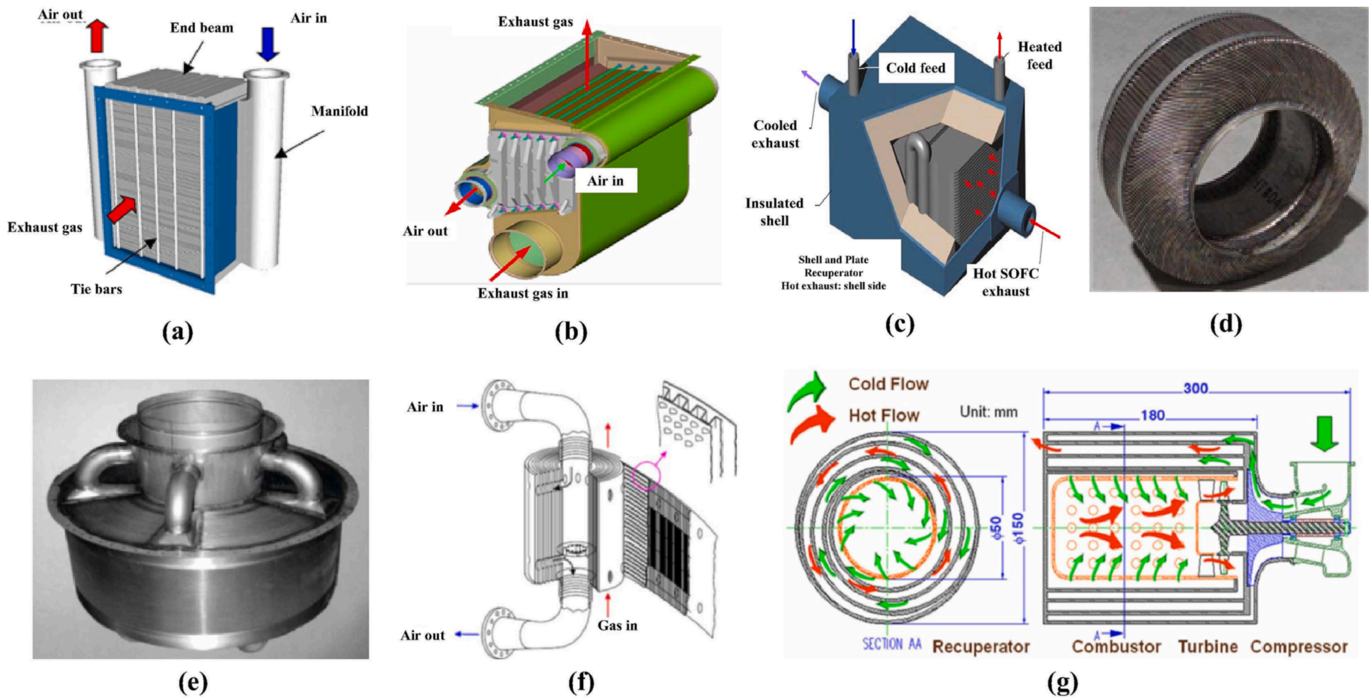


Fig. 16. Images of recuperators from RSAB (a) [124], Honeywell (b) [127], SiC (c) [128], Capstone (d) [129], ACTE (e) [125], Rolls-Royce (f) [125] and Swiss-Roll (g) [130].

(concept in the field of thermodynamics introduced by Adrian Bejan et al. a unique method/principle that asserts flow systems, whether they are natural or man-made, tend to evolve in a way that maximizes overall efficiency of flow). To centralize all these effects during recuperator designs, framework for developing optimization approaches for recuperators, considering criteria such as pressure drop, heat transfer effectiveness, system efficiency, weight, and cost, shown in Fig. 17. This pathway will be further adopted in future of recuperator designs for MGTs. This method was validated using different commercial MGT recuperator designs.

With many papers analyzed, adaptable, and flexible recuperators are essential to accommodate various applications of MGTs. Developments of alloys and new composite materials and designs of recuperators is a challenge, particularly for supercritical CO_2 turbines, which are of interest but have limited research. Coupling emission reduction with recuperators would help to meet growing environmental protection requirements. Desired characteristics for MGT recuperators include high heat transfer effectiveness (>90 %), low pressure loss (<3%), high-temperature mechanical and corrosion resistance (>650 °C), lightweight, and cost-effective construction. Ceramic recuperators outperform metallic designs in high-temperature properties, with the potential to achieve an overall efficiency of up to 40 %. Material selection and manufacturing processes, especially for ceramic recuperators, require significant effort to develop mature, reliable, and low-cost options. Laminated object manufacturing (LOM) is a potential option for ceramic recuperators. As an emerging technology, 3D printing and printed circuit heat exchanger technologies hold promise for manufacturing recuperators, especially for supercritical CO_2 applications. Another aspect to consider, MGTs exhibit dynamic performance with non-linear and large time-delay characteristics when analyzing thermal performance due to factors such as rotational inertia of the shaft, thermal inertia of the recuperator, and impeller co-working. The smaller rotational inertia of MGTs compared to large GT's makes the thermal inertia of recuperators have a significant impact on the system. Considering market values and practical limitations, in recent years, research has focused on micro recuperators for improving low-cost fabrication. Diverse types of recuperators, like SRR, offset strip finned, and wavy fin, have been extensively studied. Optimization methods like MOOP using GA and MOGA have shown promise to overall enhance the design uncertainties of recuperators coupling with MGT. Ceramic recuperators offer high-temperature properties and potential for 40 % efficiency. Ongoing research pathways aims to develop adaptable and flexible recuperators for various future applications. Advanced manufacturing technologies like 3D printing and LOM are rapidly spreading across leading MGT manufacturers. Coupling emission reduction concepts with recuperators are now considered as an essential element for environmental protection. In summary, the progress of MGT-based recuperators as a cohabited MGT research segment may be slow in the upcoming years with improving the effectiveness of recuperators when considering enhancing the thermal efficiency of MGTs, as their thermal efficiencies are currently almost at their peak.

2.9. MGT and solid oxide fuel cell (SOFC) combined research

High-temperature fuel cell systems, especially solid oxide fuel cells (SOFC) combined for efficiency improvements with MGTs. In combined MGT + SOFC, MGT produces electricity and recovers waste heat from exhaust. This waste heat, with additional fuel, to SOFC, enhancing efficiency, generating more electricity. MGT provides immediate power while SOFC generates continuous electricity and useful heat, maximizing overall energy utilization. SOFC and MGT depends on amount of excess waste heat released as byproduct during SOFC operation. Early theoretical studies explored potential of this hybrid arrangement, highlighting environmental friendliness, high efficiency, and cost-effectiveness. In 2007, MHI Japan developed 200-kW SOFC-MGT, power output of 229 kW-AC, reported world's highest-class output for this type of MGT [130]. Efficiency of 52.1 % on LHV, exceeding target efficiency 50 %-LHV. Long-term operation tested with 3,224 h, no observed deterioration in SOFC voltage, no performance degradations observed after 4 cycles of shutdown-restarts. Liu et al. (2010) [131] and Bang-Møller. C. et al., (2010) [132] numerically analyzed combining "gasifier" with SOFC-MGT. Plain SOFC-MGT achieved higher $\eta_{el} \sim 50.3$ % compared to gasification-SOFC plant (36.4 %) and gasification-MGT plant (28.1 %). Around 50 % of fuel was converted into P_{el}, 29 % used

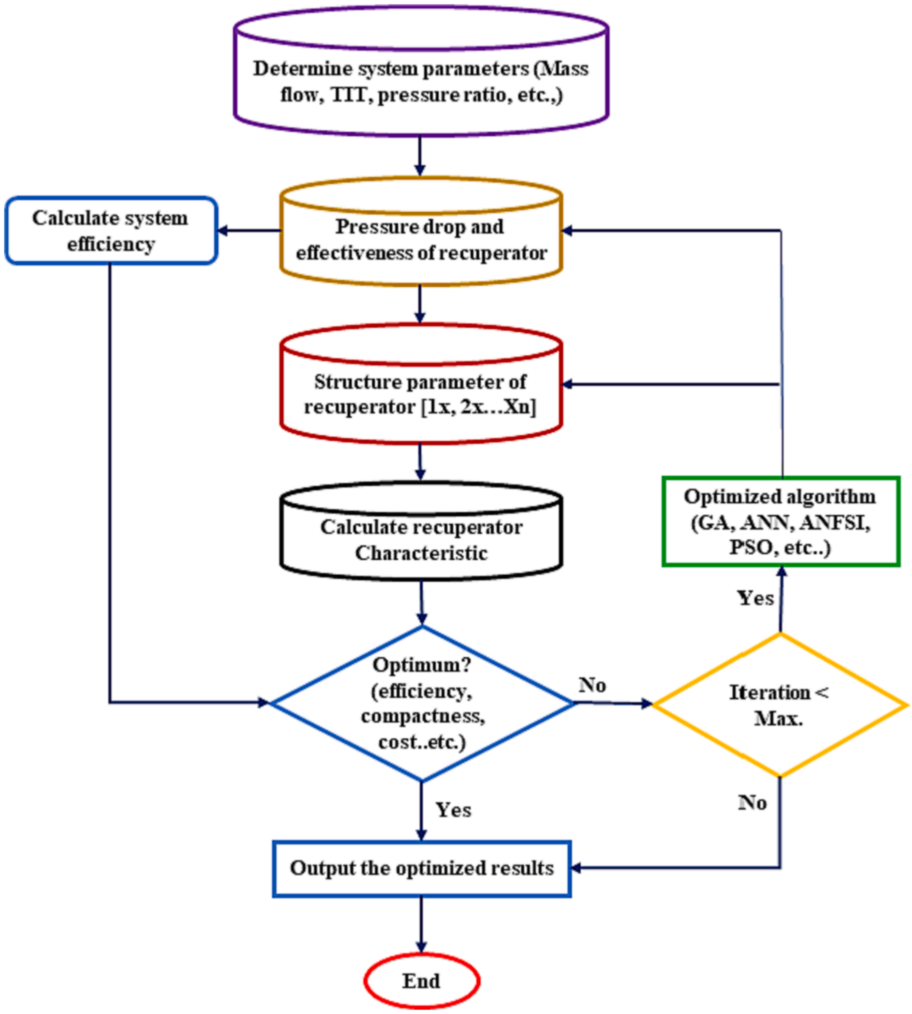


Fig. 17. General workflow chart for recuperator optimization [123].

for district heating. Another optimized hybrid CHP plant using biomass with two-stage gasification, SOFC, and MGT generated 290 kWe with maximum $\eta_{overall}$ of 58.2 % on LHV [133]. Both studies used 0-D modelling with Dynamic Network Analysis (DNA) for steady-state process modeling, which developed at Technical University of Denmark. Bakalis et al. (2012) [134] and [135] showed SOFC/MGT systems efficient and help to reduce tons of CO_2 emissions during DEGS compared to central large scale power plants. Sanaye, S. et al. [136] optimized 200 kW SOFC-MGT system achieving 60.7 % efficiency, economically competitive with LCOE of 0.057 kW/h$, and PBP of 6.3 years. Integrating a smaller 5-kW SOFC module with MGT unit reached$\eta_{overall} \sim 65$ % [137]. Zhou, D. et al. (2015) [138] simulated SOFC-MGT system with CO_2 capture, resulting 59 % efficiency and significant 99 % CO_2 capture. Off-gas recirculation assessed to enhance$\eta_{th} > 57$ % making higher power output compared to other MCFC systems. Strazza C. et al. (2015) [139] combined life cycle assessment (LCA) and life cycle costing (LCC) techniques to propose a new method assessing adverse environmental impacts with 230-kW SOFC/MGT system. Developed control methods for partially exerted loads. M. Ebrahimi et al. (2016) [140] proposed new power generation cycle combining SOFC, MGT, and ORC (in Fig. 18 (a)). The HRSG unit between MGT and ORC cycles employed pinch technology, curving temperature profiles of exhaust gases and ORC fluid (Fig. 18(b)) to minimize temperature differences (pinch point) denoted as ΔTpp. Also, an efficiency analysis assessed influence of 10 design parameters on cycle behavior using a spider diagram (Fig. 18(c)). Reformer temperature, fuel utilization, steam-to-carbon ratio (STC) exhibited significant impacts on η_{el}. Current density increments (I) had negative influence, cell and ORC working pressures positively affected MGT efficiency. System achieved maximum η_{el} of 61 % and $\eta_{overall}$ of 65.77 %, showing significant improvement compared to conventional systems.

Barelli, L. et al. (2017) [141,142] investigated flexibility of using SOFC/MGT hybrid systems in Micro-Grids. System reached$\eta_{average} \sim$ 54.5 % on daily basis, SOFC and MGT sharing electrical load up to 42.8 %. Otomo, J. et al. (2017) [143] designed hybrid power train using segmented-in-series tubular SOFC stack integrated with MGT, but it was not successful. Marta G. et al. (2018) [144] reported installation of 174 kWe SOFC-MGT fed by biogas at Collegno WWTP (DEMOSOFC European project) covered 30 % of site's electrical consumption. Proposed co-gasification system by woody biomass and animal manure with MGT-SOFC, achieving η_{th} of 55 %. Neutralizing primary energy and CO_2 emissions embodied in manufacture made operational savings, reduced PBP, and LOCE. Perna A. (2018) [145] numerically assessed hybrid BG-SOFC/MGT co-generation plant, achieving$\eta_{el} \sim 35$ % and 88 % co-generation efficiency. Pressure ratio's impact was minimal, optimal results reached P_r of 4.5 and S/C of 0, producing$P_{el} \sim 262$ kW (180 kW from SOFC), $P_{th} \sim 405$ kW with$\eta_{el} \sim 35$ %, and 88 % cogeneration efficiency. To maximize P_{el}, a 20 % S/C yield 317 kW of P_{el} (238 kW from SOFC), 354 kW of $P_{th}\eta_{el} \sim 38$ %, and 80 % cogeneration efficiency. Comparing hybrid BG-SOFC/MGT configuration to BG-SOFC plant, hybrid system offers significantly improved η_{el} (35 % vs. 24 % for S/C = 0; 38 % vs. 28 % for S/C = 20 %). Despite utilizing SOFC off-gases for air

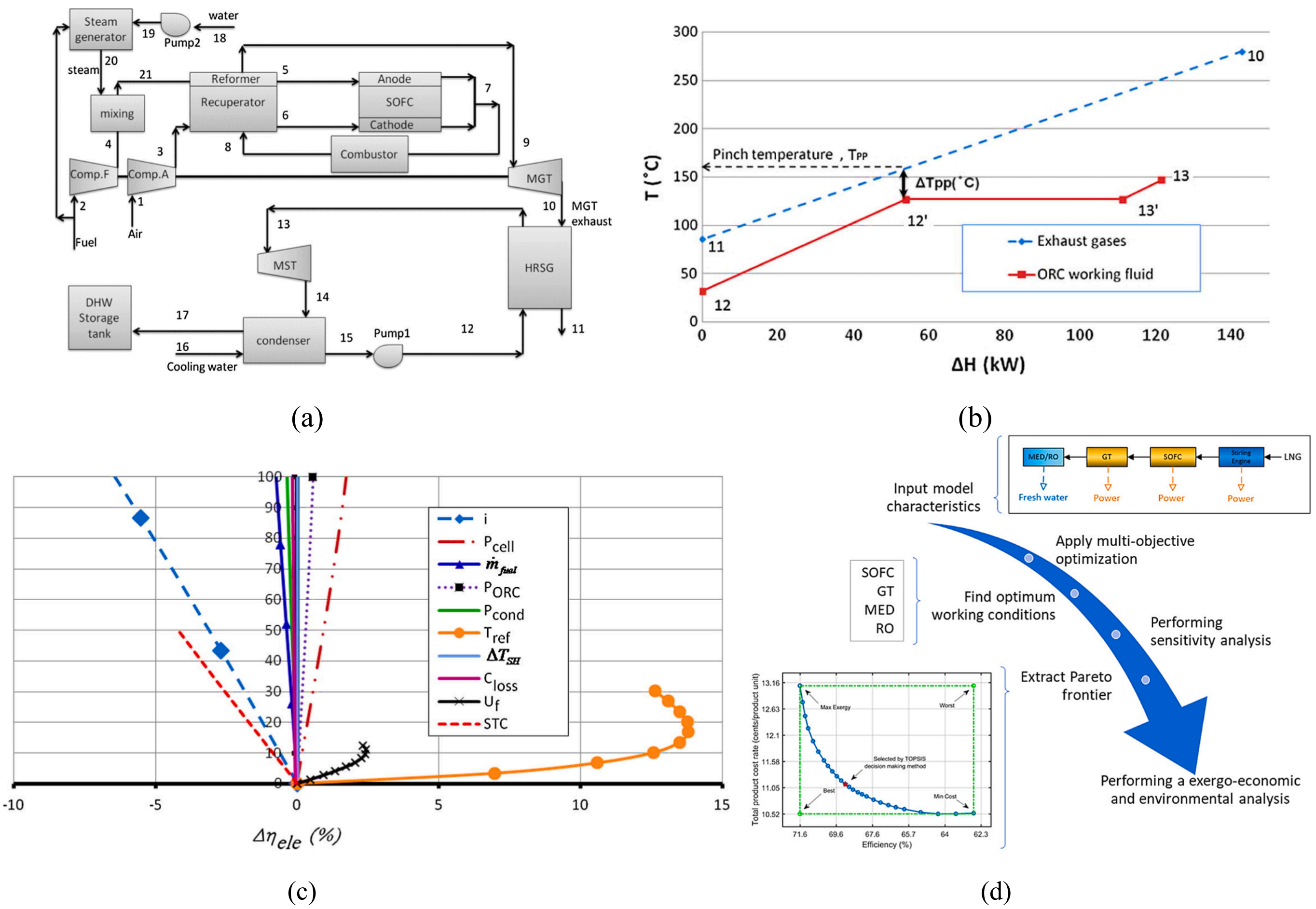


Fig. 18. (a), (b) The pinch technology illustration for the HRSG and (c) Spider diagram of sensitivity of η_{ele} of the cycle versus 10 design parameters. [140] and Fig. 41: Workflow and methodology of the thermo-economic study and Multi Objective Optimization Process (MOOP) [147] and M. Bahari et al., (2021).

temperature elevation, overall CHP efficiencies remained comparable. Emphasizing hybrid's ability to efficiently exploit primary energy by enhancing η_{el}. Hossein K. et al. (2019) [146] assessed a CHP plant with a gasifier, SOFC, MGT, and ORC, achieving 35.1 % $\eta_{overall}$ and 10.2 $/h cost rate, generating 6660 GWh of electrical energy and 1140 GWh of thermal energy from Iran rice straw. Huailiang Y. et al. (2020) [80] conducted both conventional and advanced exergoeconomic analyses for SOFC-MGT systems. Highest cost rate in conventional analysis associated with SOFC ~ $4.62/h, advanced analysis showed inverters had highest cost rate at $1.065/h. Advanced method provided complex theoretical methodology for SOFC-MGT system, its complexity was major drawback. To address this, same author [147] proposed systematic approach using CCHP SOFC-MGT system combining exergoeconomic method proposed by M. Bahari et al., (2021). Pareto frontier curves generated to illustrate trade-offs between objectives, for example, total product cost rate and efficiency. Best matching point through Pareto frontier found using TOPSIS decision-making method (In Fig. 18(d)). ProvidedP_{el} ~ 300.0 kW, cooling ~ 7.358 kW, and heating ~ 8.757 kW with 0.1715 kg/s potable water production rate. Total cost calculated as $9.838/hour while total cost per unit exergy of 14.75 $/GJ under design conditions, similar methodology adopted by June Pedro et al., (2023) [182] for MCFC-MGT thermoeconomic evaluation. Overall, several new methodologies and innovative approaches have proposed to further enhance efficiency and reduce costs, making SOFC-MGT systems attractive for various applications, including cogeneration plants, micro-grids, and WWTP. However, application of SOFC-MGT in cogeneration may acquire higher costs (CAPEX and OPEX) compared to other MGT systems, necessitating careful consideration of return on investment, PBP, NPV. Ongoing research pathways focusing SOFC-MGT with different settings and exploring alternative fuels seeking better performance. With continued advancements, SOFC-MGT combined research likely to progress steadily in future to enhance value of MGT.

2.10. MGT and Non-Biofuel related combustion and emissions based research

Research on "fuel adaptability" for MGTs, have own advantages and disadvantages. To minimize GHGE and enhance performance many studies focusing optimizing MGT performance through design changes, MOOP methods, changing control strategies, part-load optimizations [183–187] but the trend will no longer exist with "net-zero" emission targets. K.A. Al-Attab et al. (2017) [148] assessed MGT numerical model (Referring to original article [148]; Fig. 1*(b)*) utilizing low-quality syngas for thermal applications. Turbocharger based MGT with pressurized cyclone combustor and annular tube HRU achieved stable syngas combustion with low emissions (NOx < 250 ppm, CO < 15 ppm). With TIT < 700 °C, with 34 kW hot air thermal output, η_{th}~37.8 %. During MGT startup, auxiliary LPG fuel preheated chamber before syngas introduction. After 15 min in dual fuel mode, LPG cut off to compare combustion inside pressurized cyclone combustor (PCC) with and without LPG (Referring to original article [148]; Fig. 4). PCC temperature profiles (T1-T4) showed dual fuel mode's flame shifted lower, higher temperatures > 1150 °C (T4) at chamber inlet. Combustion finished in lower chamber, cooling gas at exit (T1), expected for PCC's LHV fuel design. Syngas combustion extended flame to (T3), reaching 1100 °C. Syngas combustion stability was acceptable, with minor temperature fluctuations due to syngas flow and quality changes. Downside being system showed only potential attraction for hot air (thermal) applications only, but electricity being more useful form of work. E.C. Okafor et al. (2019) [149] numerically examined CH_4-NH_3 combustion in MGT, rich-lean combustion reduced NOx emissions to 49 ppmv, CO to 2 ppmv, and achievedη_{comb} ~ 99.8 %. J.-M. Bellas et al. (2019) [150] evaluated MGT performance under selective EGR (S-EGR), achieving 10.1 % CO_2 concentration in flue gases but decreasing η_{el} with partial load incomplete combustion but S-EGR reduced NOx. In S. Giorgetti's [151], MGT coupled with CCP analyzed combining EGR and mHAT concepts. Humidified MGT at full load reached η_{el} of 24 %, compared to 21.3 % traditional MGT with CAP. Another study S. M. Choi et al., (2020) [152] proposed "Schlieren" visualization and infrared (IR) (Fig. 19. (I)) signal analysis to study plume ejected from MGT nozzle using IR camber. Nozzle shape significantly affected infrared signal emitted from exhaust plume. IR signal decreased as nozzles aspect ratio (AR) increased. With Schlieren flow visualization cone nozzle had uniform flow pattern, square nozzles showed bright triangular pattern in dispersed plume. Sample image in Fig. 19 (II) presents shapes. Size of bright triangular pattern decreased as AR of square nozzles increased. Triangular shape of core plume played leading role in temperature diffusion with surrounding air. 3-types of exhaust plume models identified. Homogeneous plume (cone nozzle), intermediate plume (AR2 square nozzle), and two-dimensional (2-D) plume with hot core (AR5 square nozzle). Fig. 19 (III) compares exhaust plume temperatures for different nozzles. At Z = 15 mm, cone nozzle's max temp showed 441.1 °C, S-shaped nozzles ~ 454.3 °C. For Z = 280 mm and Z = 600 mm, higher AR of square nozzles reduced max temps compared to cone nozzle. Average temp drop was smaller. For AR5, Z = 280 mm max temp decreased 50.3 %, avg temp 19.0 %. At Z = 600 mm, max and avg temps dropped by 40.2 % and 19.0 %. S-shaped nozzle had higher max temp but similar avg temp as AR5, implying less gas mixing but wider plume spread. Fig. 19 (IV) illustrates vertical plume temp changes at Z = 15 mm, X = 0 mm. Cone nozzle showed almost no temp deviation at center, while AR5 nozzle had drops in Y = 10 mm and Y = 20 mm regions above and below center. These findings provide outside-to-inside information for optimizing MGT exhaust systems.

Important study Vittorio B. et al. (2022) [153] investigated direct NH_3 combustion in 100 kW MGT, full and part-load conditions. Used numerical modelling by THERMO Flex v29.0® software, validated by literature-based NG test results. Replacing NG with NH_3 shifted compressor-turbine matching, resulting lower air and flue gas flow rates with NH_3 lower LHV. Referring Fig. 20(I), for 100 % NH_3, η_{el} decreased 0.5 %, exhaust gas heat recovery improved, maintaining η_{total} between 74.5 % and 79.1 % across load range·NH_3 enabled zero CO_2, adjustments in compressor-turbine matching needed. At rated power, air and flue gas flow rates decreased 4.3 %, 2.8 %, overall cycle P_r increased 2 %. Burning NH_3 required turbomachinery equilibrium point adjustments, NOx emissions needed to pass through SCR. Experimental results needed for a conclusive assessment. Importantly, results in Fig. 20(e), (f) directly compare MGT performance using NG and NH_3 as fuel. Part-load strategy had minimal impact, confirming earlier findings·NH_3 in MGT, slightly lowered η_{el} by 0.5 %, but $\eta_{overall}$ remained similar to NG scenarios with improved heat recovery. However, at P_{el} < 60 kW, both fuels showed noticeable η_{el} drop as TIT decreased with load. Since reduced η_{el} led to lower exhaust $\dot{m}$ and P_{th} at part-load, decline in $\eta_{overall}$ under derated conditions roughly consistent regardless of fuel type and part-load control.

J. Lu et al. (2021) [154] investigated combustion characteristics and pollutant emissions in 100 kW MGT using methane doped with

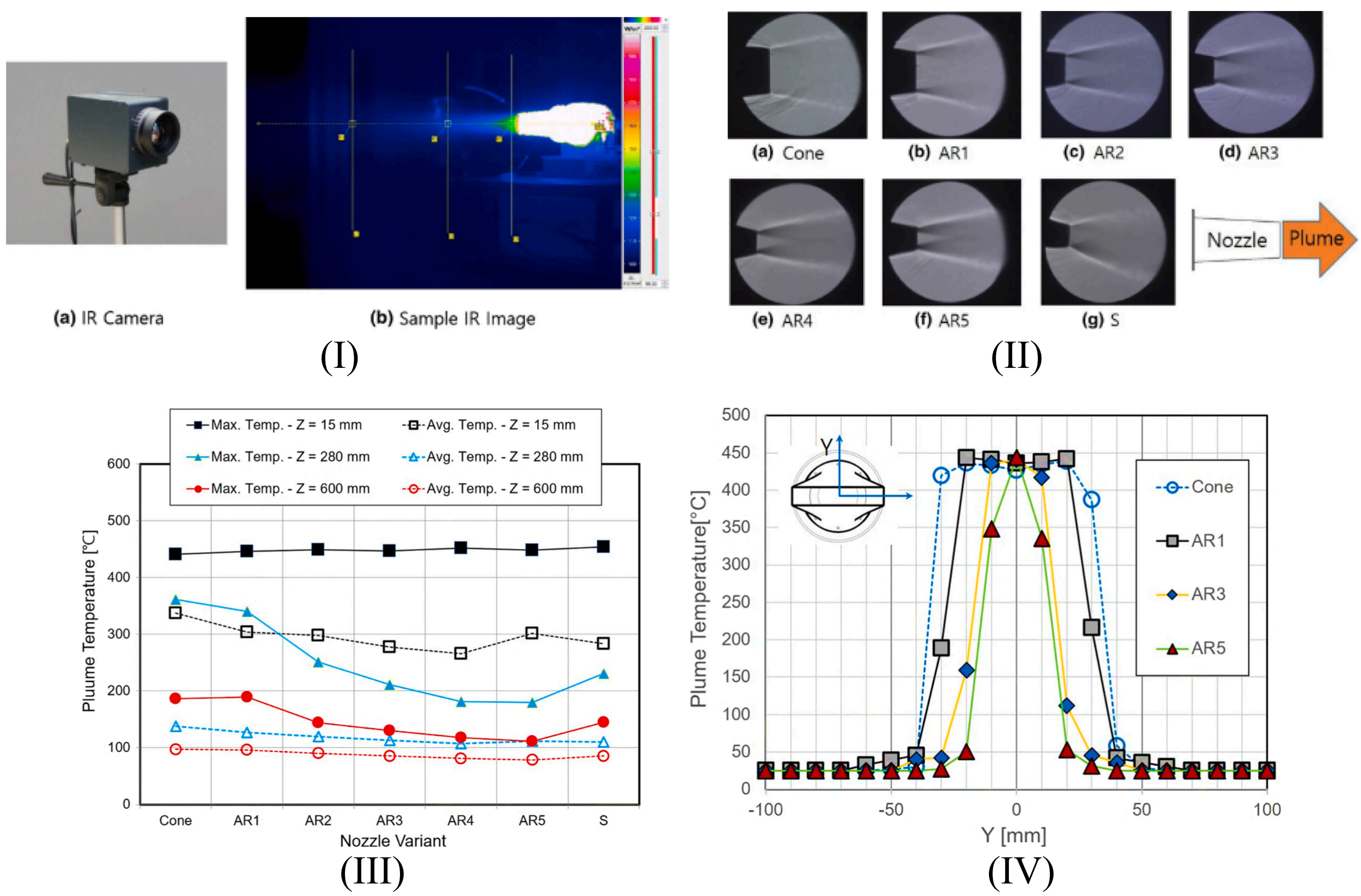


Fig. 19. [I] (a) IR camera used and (b) Sample IR image of the experiment [II] Shapes of Nozzles analyzed in the study [III] Plume maximum and average temperatures [IV] Plume temperature variations in the vertical direction at X = 0 mm and Z = 15 mm [152].

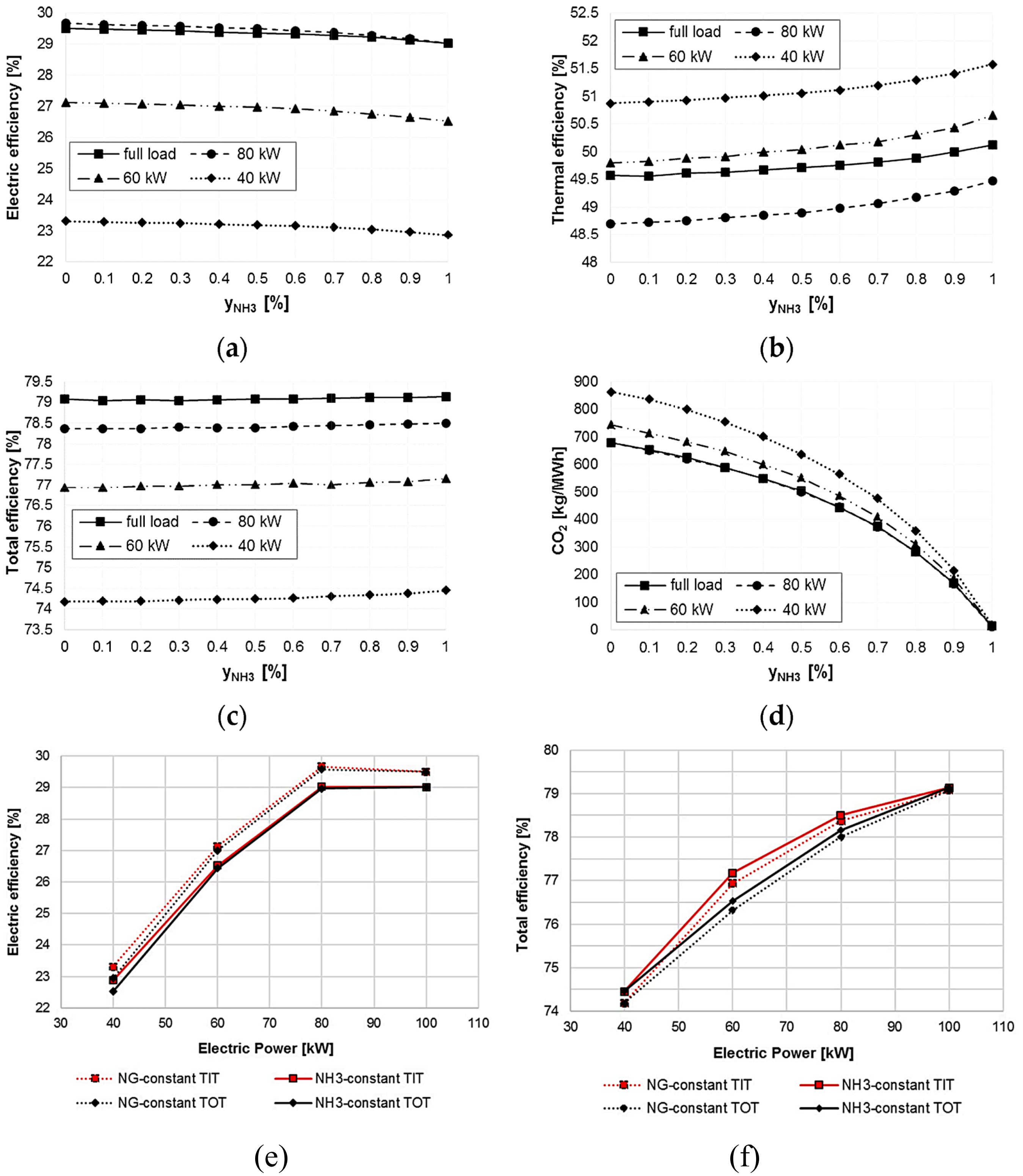


Fig. 20. Effects of NH_3 feeding, at distinct levels of power output, on: (a) electric efficiency; (b) thermal efficiency; (c) total efficiency; (d) CO_2 emission intensity. Effects of replacing NG with NH_3, by varying part-load control strategy, on: (e) electric efficiency, (f) thermal efficiency [153].

hydrogen (CH_4/H_2). Different air flow distribution schemes studied, increasing amount of premixed air led higher NO concentrations. At 50 % premixed air, NO concentration reduced 0.717 ppm. Fabrizio R. et al. (2021) [155] numerically analyzed MGT plant using H_2 and cycle humidification, initially the base MGT system modified shown in Fig. 21 (a). Two components added, an economizer and heat exchanger, water is heated using recuperator exhaust, and evaporative cooler used where water mixed with compressed air. Comparison in Fig. 21(b), (c). Adding H_2 to methane and biogas had minimal impact on power and efficiency, water addition significantly improved latter factors, also increased P_r for both compressor-turbine, resulting higher turbine mass flow, lower compressor mass flow. This enhances W_t, reduces W_c, leading to power

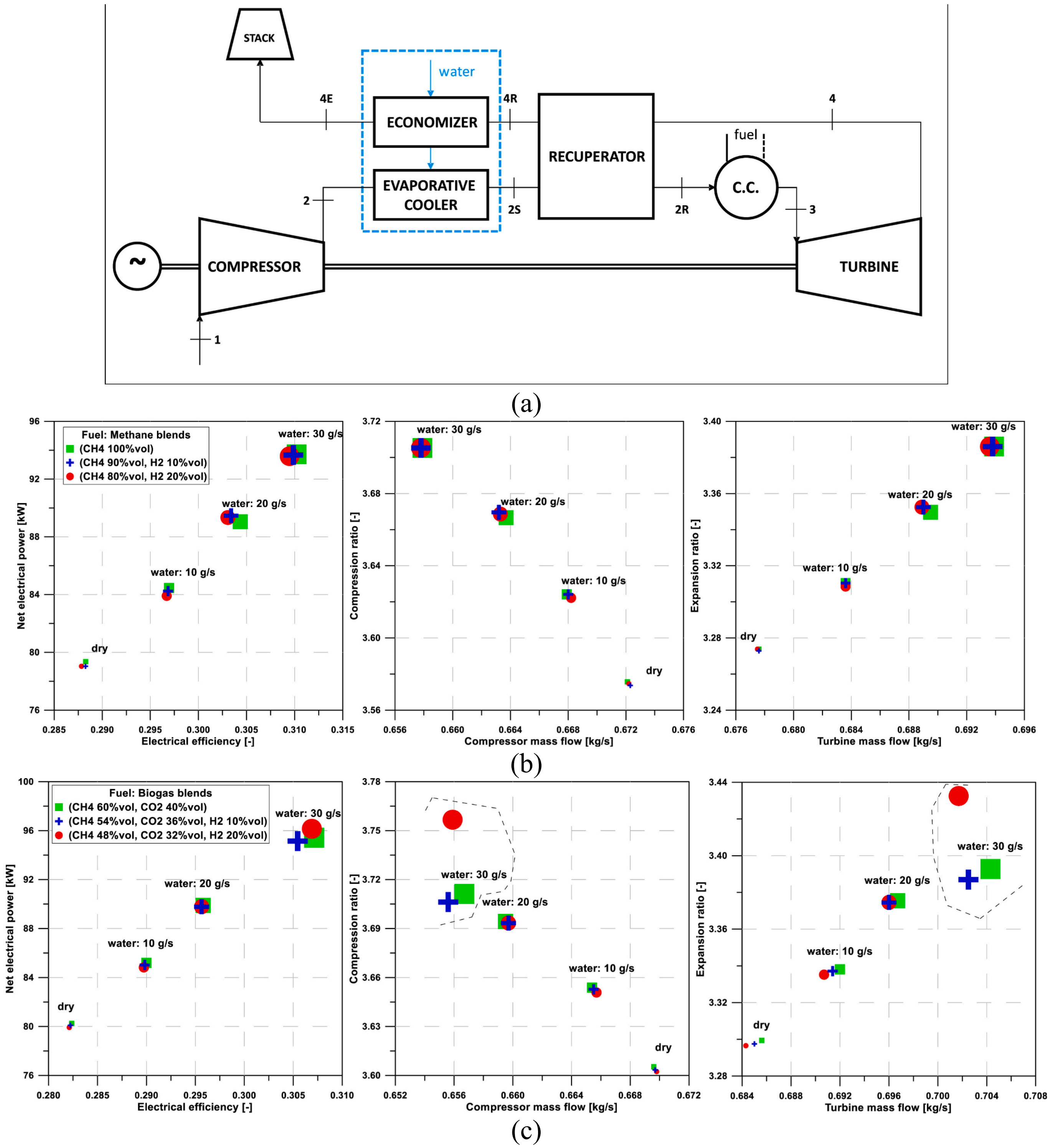


Fig. 21. (a) Humid Air Turbine cycle layout (b) Methane blends (c) Biogas blends [155].

and efficiency with h-MGT. Humidifying extended MGT operating range, transitioning from running line to surface for each fuel, while keeping total temperature (TOT), TIT constant. H_2 enrichment 30 % vol. achieved safely with steam injection. Air humidification improved net power delivered and $\eta_{overall}$, improving performance and environmental benefits.

Fabrizio R. et al. (2022) [156] numerically studied steam injection effect on maximum allowable H_2 content blended with CH_4 in Turbec T100. Steam injection increasing H_2 content from 10 % to 35 % by vol. without harming mass and energy balance and decreased NOx. W. Shen et al., (2022) [157] studied effects of EGR to enhance part-load performance and flame stability. They combined EGR with adjustable fuel feeding combustor (In Fig. 22. (I)) in 300 kW MGT. Experiments conducted to analyze impact of EGR on Heat Release Rate (HRR) under different load ratios (50 % – 100 %) and EGR ratios (0–20 %). EGR effectively reduced overall turbulence flame decay (OTFD) at high load ratios and improved flame stability. Frequency analysis shows strong correlation between flame frequency and turbulence characteristic

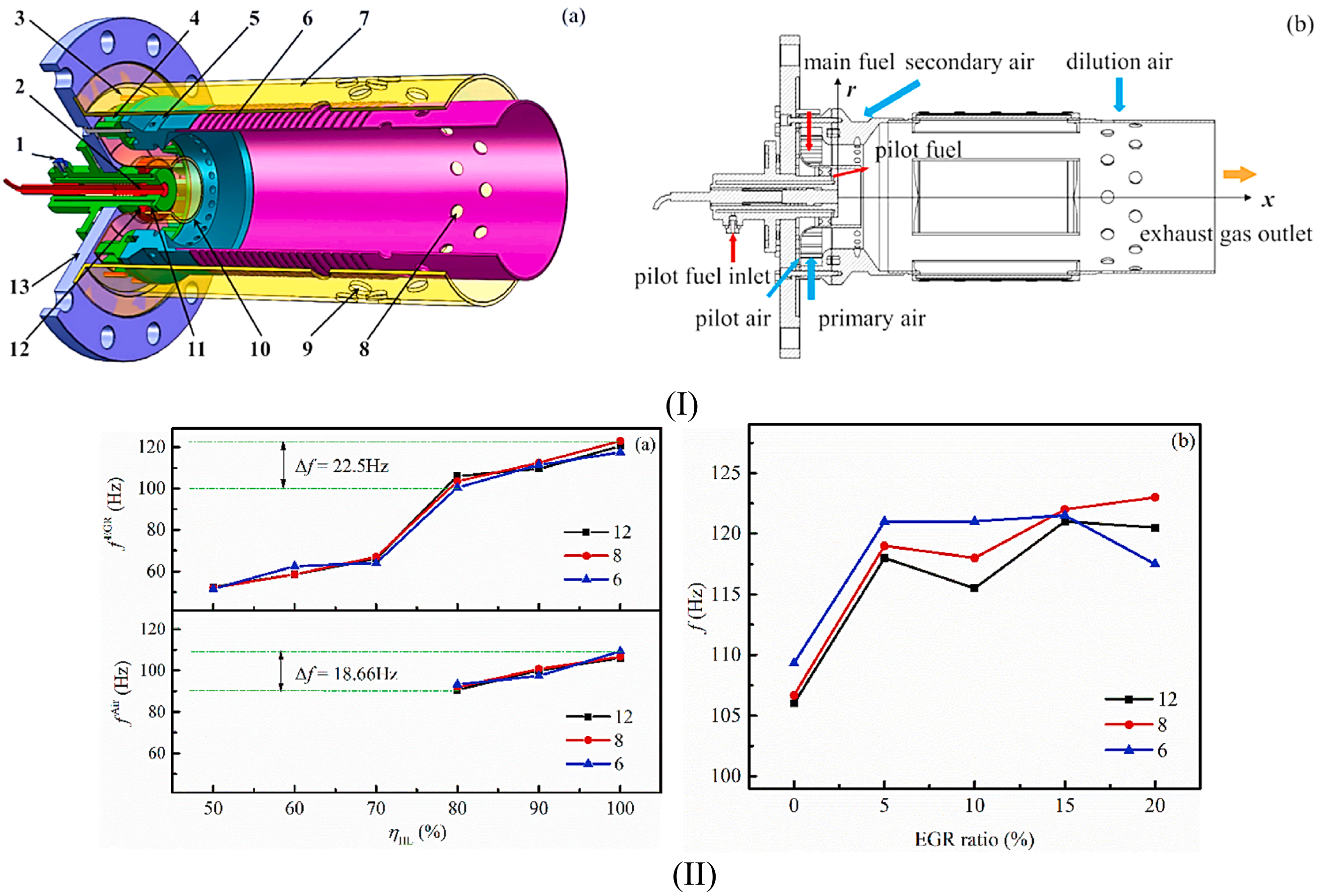


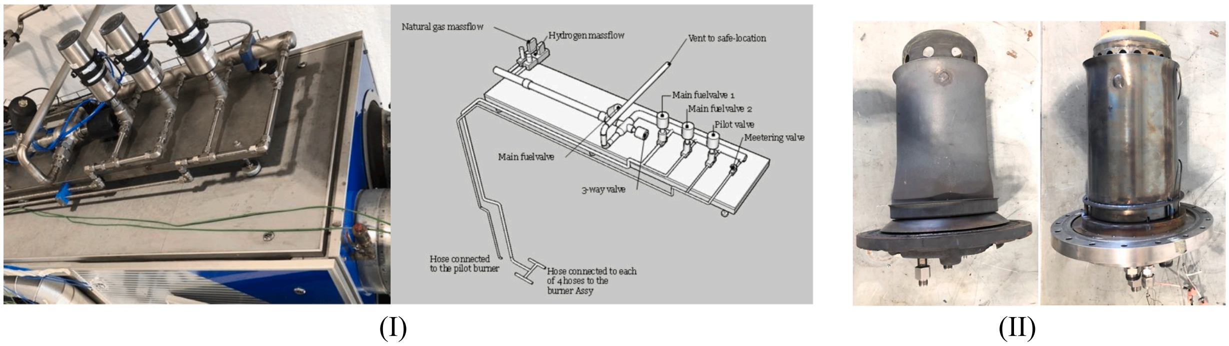
Fig. 22. (I) Combustion chamber layout (1. Pilot fuel inlet 2. Igniter 3. Main fuel tube 4. Primary air swirler 5. Secondary air swirler 6. Liner 7. Casing 8. Dilution hole 9. Casing hole 10. Premixed sleeve 11. Pilot fuel nozzle 12. Pilot air swirler 13. End cover); (b) Structural diagram of combustion chamber with observation windows. (II) The effect of EGR on the HRR characteristic frequency [157].

frequency. EGR significantly enhanced combustion part-load performance of MGT. Comparison with OTDF reveals lower OTDF with smaller spatial distribution uniformity (C_{su}) with reduced peak HRR and uniform distribution, preventing hot spots. Fig. 22 (II) (a); frequency differences between air and EGR conditions, with lower frequency under EGR. Flame frequency characteristics remained stable without mixing or EGR introduction. Fig. 22 (II) (b) demonstrates notable frequency increase with EGR, but minimal changes within EGR ratio range. Thus, flame dynamics in MGT showed minor changes with EGR.

Banihabib R. et al. (2022) [158] developed an MGT operating CH_4 and H_2 blends with collaborating, University of Stavanger (UiS) and the German Aerospace Centre (DLR). They modified T100PH MGT with new FLOX based combustor and novel fuel train developed for H_2 applications (In Fig. 23 (I)). The F400s FLOX® combustor generally produces low NOx, flameless combustor with proven fuel flexibility, capable of running on H_2. Previously this combustor only tested under atmospheric experiment on 100 % H_2, its H_2 burning capability actual pressurized conditions inside an MGT verified during this testing. Varying H_2 content 50 % to 100 %, power output changed 35 kW to 100 kW. Fig. 23 [III] (a); higher H_2 content associates, lower CO, pure H_2 exhibited zero CO. Deviations from trends occurred from 55 % H_2 tests with valve modifications impacting η_{comb}, and CO rates. Fig. 23 [III] (b); NOx under various H_2 contents and power outputs. Generally, NOx rose with higher H_2 %, except for cases around 55 % H_2 due to specific valve settings. Fig. 23 [III] (c) examined hydrogen's impact on engine η_{cycle}, revealing similar efficiencies across full H_2 content and increasing efficiency with power output. Ambient conditions affected constant power due to inlet temperature. Maximum NOx with pure H_2 under full load ~ 25 ppm. Produced 64 ppm ~ NOx with 15 % O_2, lower than regulated value reported. H_2 injection didn't affect η_{el}, but increasing H_2 share reduced GHGE and improved η_{comb}.

Elsayed B. et al. (2022) [159] investigated impact of saturated fogging (inlet fogging) and overspray on 10 kW MGT under part-load conditions (experiment setup in Fig. 24 (I)). Inlet air temperature rose 22 to 38 °C resulted power output reduction by 11.4 %, 8.3 %, and 6.5 % for 30 %, 50 %, and 70 % loads. At overspray (OS) level 2 %, in Fig. 24 (II): (a) power output, SFC aligned, showing increased generated power and SFC. Most notable enhancements seen OS 2 %, with power output improved 14.41 %, 11.19 %, and 8.73 % at 30 %, 50 %, and 70 % loads. Simultaneously, Fig. 24 (II): (b) SFC improved 13.11 %, 10.52 %, and 7.95 % at corresponding loads. This improvement attributed to increase in humidity ratio 0.0062 to 0.0285 kgw/kga. Saturated fogging increased output power 9.32 % at 30 % load, with 14 °C temperature drop. However, at 50 % and 70 % loads, power output decreased 6.86 % and 4.9 %. At same partial loads, SFC improved 13.11 %, 10.52 %, and 7.95 %. Inlet fogging and overspray reduced NO, and increased CO. Benefits of fogging and overspray decreased with increasing load while maintaining constant fuel consumption during cooling processes.

Future of MGT in relation to fuels and emissions research holds great promise as researchers explore alternative fuel options and innovative combustion techniques. Studies have investigated use of various fuels, such as vegetable oil, synthesis gas, biogas, and H_2, assessing their combustion characteristics and emissions with MGT's. H_2 and NH_3 have shown potential for reducing CO_2 and offer cleaner energy. Efforts to utilize low-quality syngas, fuel enrichment, advanced control strategies aiming improving $\eta_{overall}$. Factors like humidification, steam injection, EGR studied to enhance combustion stability and reduce emissions.



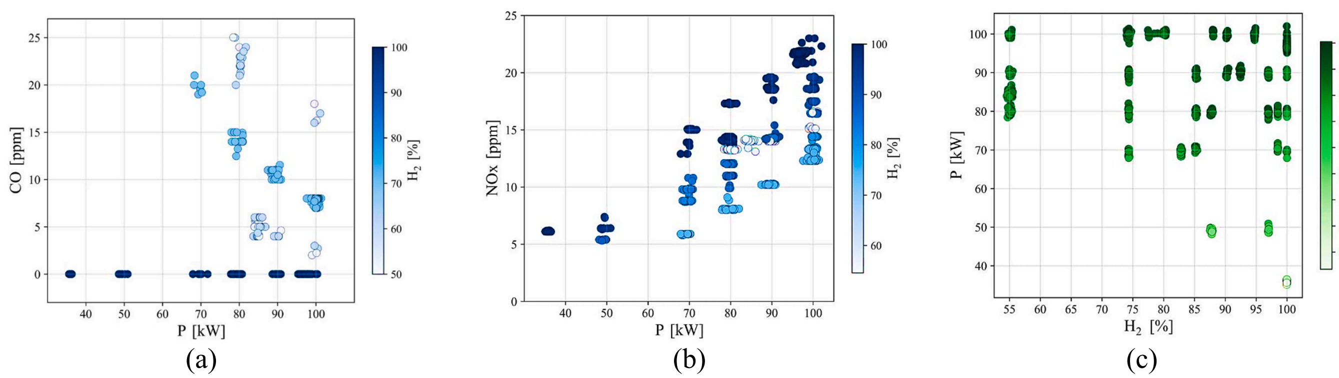


Fig. 23. (I) Fuel train for H_2/methane fuel supply and mixing (II) The original combustor was installed on T100 (left) compared to F400s fuel flexible combustor installed on test rig (right) (III): (a) CO (b) NOx emission in range of power output with different H_2 content in fuel (c) Electrical efficiency production in a range of power outputs with respect to H_2 content in fuel.

Future of MGT technology depends on degree of optimization using alternative fuels, exploring innovative combustion methods, adopting A. I based control systems, ultimately leading to cleaner and efficient power generation reducing environmental harm. Overall, fossil fuels-based (Carbon based fuels) research activities have seemed to come to an end and this area of advancements on MGTs are declining and will have less potential for future research activities.

2.11. MGT: Biofuels based combustion and emissions research

Solution to problems facing with carbon-fuels and emissions, promising alternative is to use biofuels. Biofuel usage in MGT operations not extensively researched until recently. Mainly "Bioliquids" show greater potential growth with MGT sector. Studies explored combustion of highly viscous bioliquids, necessitating adaptations in various MGT components. Also investigated blends of Fischer-Tropsch pyrolysis bio-crude (FPBO) with aviation or diesel fuels and ethanol. Liquefied wood derived from forest residues extensively analyzed for combustion, formulations without low viscosity biofuels tested. Glycerol and glycerol/diethylene glycol mixtures been explored. There is potential for HTL biocrude, direct-fired MGT experiments, and test results are lacking. However, technical advancements cover methodologies for investigating non-upgraded HTL biocrude in MGTs. The summarized research on MGT utilization [188–222] presented in Appendix D to conceive the length of article.

Usman Ali et al. (2017) [160] numerically modeled effects of integrating amine-based post-combustion CO_2 capture and EGR unit with MGT. M. Renzi et al. (2017) [161] analyzed 100 kW MGT using biomass-derived "synthesis gas" (S) fuel. LHV of forestry syngas (S gas) ~ 9.54 MJ/Nm^3, causing reduced $\dot{m}$ in compressor and risk of compressor stall. Turbine's corrected $\dot{m}$ increased (0.1 %) with higher fuel flow rate. At rated speed, η_{com} increased 0.73 %, $\eta_{turbine}$ decreased 0.2 %. MGT $\eta_{overall}$ reduced 5 % with S gas compared to NG. Steam injection increased power output and efficiency for both fuels. S gas reduced NO_x by 75 % but increased CO. MGT fueled biogas systems [162,163] numerically modeled using PEPSE-GT software, showed $\eta_{overall}$ 26–27 % at higher load. Experimental studies [164] biogas fuels in MGT, power outputs ranging from 170 kW to 70 kW at different fuel mixtures, without clear indication of fuel composition. Some studies [164] used liquid biofuels in MGT combustor, resulting reduced emission levels compared to fossil fuels, proposed solutions for reducing NO. F. Chiariello et al. (2013) [165] studied different straight vegetable oil (SVO)-fossil fuel blends, focusing pollutant emissions of 30 kWe MGT, analyzing NO_x, CO, and particulate matter emissions. These emissions showed no significant differences across different fuels and load conditions, constant overall turbine behavior. In Fig. 25 (a), global PM emissions graphed (15 % of O_2). PM varied with load and blend; higher emissions observed at part load with small presence (10 % v/v) of SVO blends. PM higher for SVO (Blend A and B), with rapeseed oil showing 3x-times higher emissions and sunflower oil blends (Blend C and D) over 50x-times higher emissions compared to pure JET A1. PM levels are independent of SVO concentration in fuel blends. Sunflower oil blends exhibited higher soot compared to rapeseed oil blends.

Differences in PM attributed to chemical structure of vegetable oils. SVO (Straight Vegetable Oil) benefits as bioliquid with biodegradability, renewability, low sulfur content. However, its viscosity is significantly higher than diesel but lower than FPBO, HTL biocrude, or liquefied wood. As a solution, blending SVO with diesel or preheating can reduce viscosity. Preheating SVO to 90 °C reduced viscosity by factor of 6x, making strong candidate substituting conventional MGT fuels. With HHV than pyrolysis oil, SVO could use in stationary combustion. Like other bioliquids, SVO can undergo further processing to enhance quality, reduce viscosity, and increase heating value. Table 6 (a) summarizes key properties of different types of SVO used with MGT combustion. Bio-alcohols and biodiesel frequently uses blending with other bioliquids enhancing viscosity and heating value for MGT combustion. Not categorized as bioliquids themselves, their role in blending is significant. Table 6 (b) compares properties of bio-alcohols (ethanol, glycerol, crude

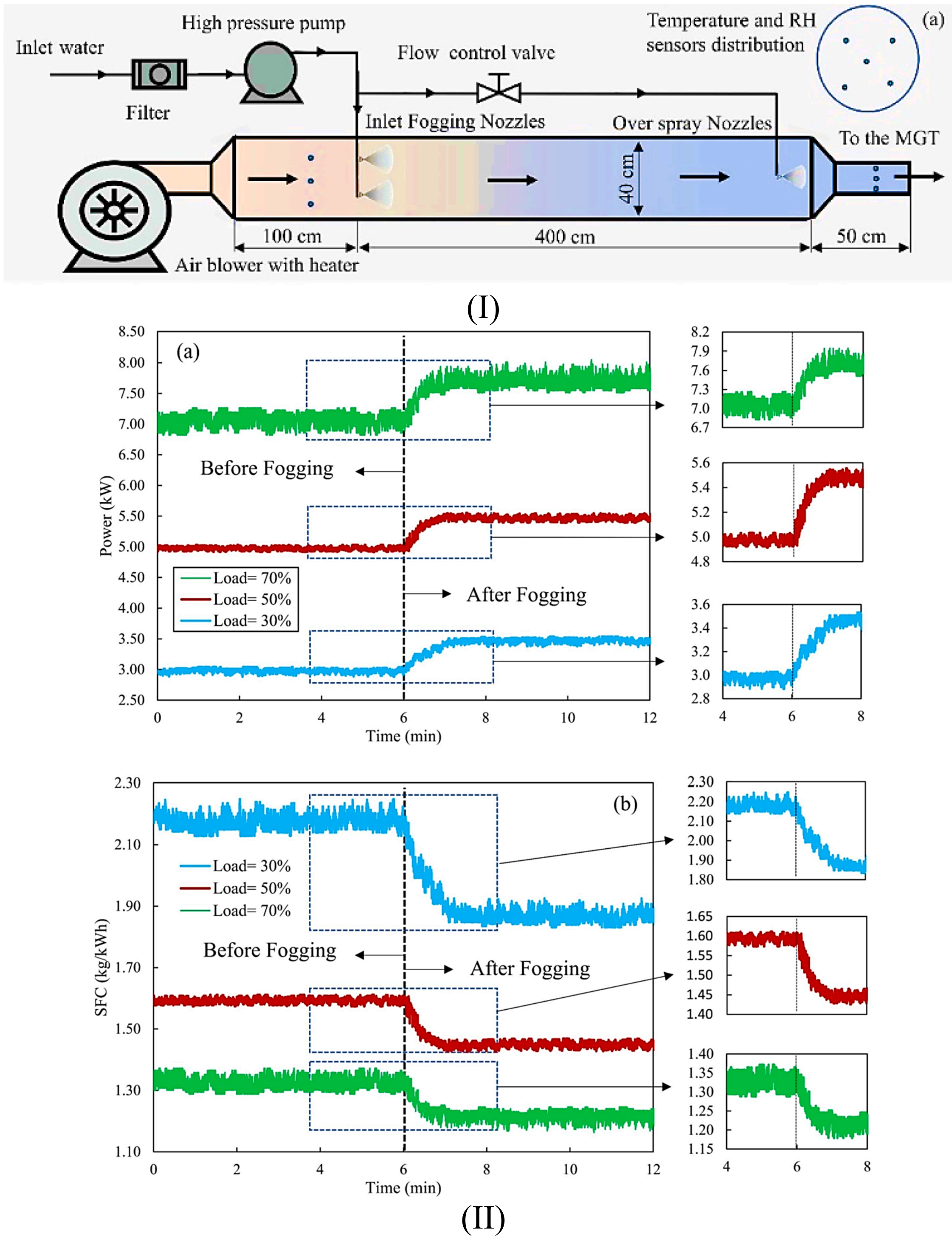


Fig. 24. (I) MGT combined with the applied fogging cooling system and nozzle arrangement patterns with overview of testing system design (II) Variation of (a) power output and (b) specific fuel consumption with time for 2 % overspray (OS 2 %) [159].

glycerol) and biodiesel, with solubility in bioliquids like FPBO. Data sources for ethanol, glycerol, crude glycerol, and biodiesel properties are provided, offering insights into their characteristics and potential utilization techniques.

H. Nikpey et al. (2014) [166] studied MGT fuel flexibility using biogas. Numerical modeling uses IPSEpro®, simulated a wide range of biogas compositions varying CH_4 % (10 %, 45 %, 65 %). Mass flow and P_r decreased with biogas compared to NG, also surge margin reduced. η_{el} decreased with decreasing CH_4 % in biogas. $\eta_{overall}$ dropped < 1 % for biogas with 45 % CH_4. Biogas had negative effect on heat recovery capability in recuperator, HRR declined with decreasing CH_4. J.L.H.P. Sallevelt et al. (2014) [167] experimented effect of biofuel viscosity on η_{comb} in MGTs. Compared SVO with biodiesel (BD). Lowering fuel viscosity improved spray quality, leading faster droplet evaporation, more complete combustion. CO decreased linearly with decreasing viscosity for both fuels. Upper viscosity limit for pressure-swirl nozzle ∼ 9 cP. Above this value, incomplete droplet evaporation caused excess unburned fuel in exhaust gas. Increased load, burning biodiesel, reduced

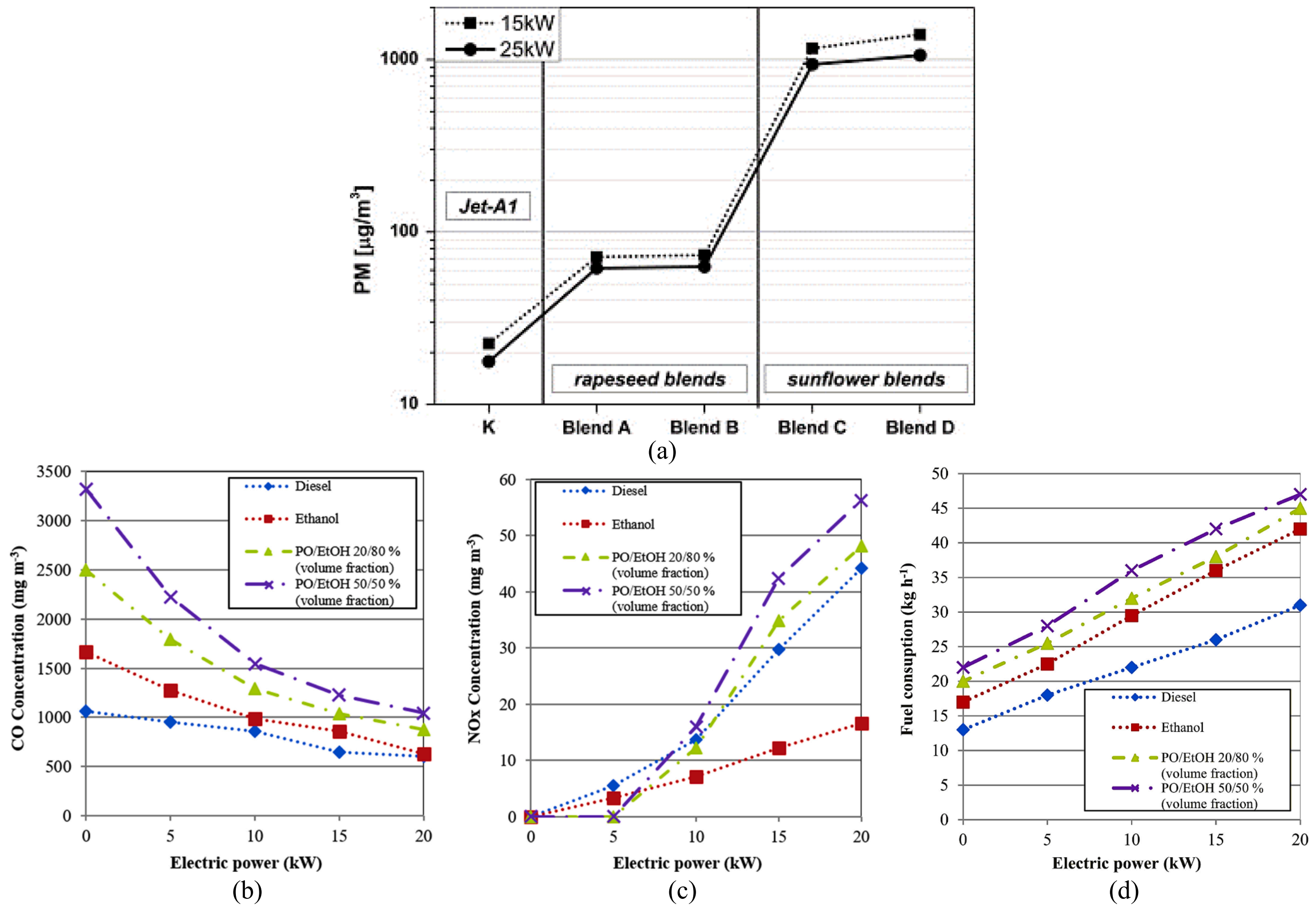


Fig. 25. (a) Global PM emissions (referred @15 % of O_2) [165], (b) CO emissions, (c) NO_x emissions, (d) SFC (normalized at 15 % O_2 in normal conditions at 273.15 K) of the selected fuels at different electrical load [169].

CO but using SVO increased CO as load increased. Kim. S. et al. (2017) [168] numerically examined biogas-fueled MGT and ORC operated with low-grade biogas. 1000-kW MGT coupled with 150-kW ORC setup utilized MGT exhaust gas. Power output of 7.4 MWh/year from MGT with CHP, 8.5 MWh/year from ORC, and 9.0 MWh/year for both ORC and MGT-CHP combined. M. Buffi et al. (2018) [169] experimented, Fast Pyrolysis Bio-Oil (FPBO) in MGTs using blends of FPBO and ethanol. FPBO/ethanol blend 20/80 % and 50/50 % vol. tested. Higher FPBO content in blend increased CO and NO_x. Increasing power output, CO reduced, but NO_x increased. Fig. 25 (b) and (c) present CO and NO_x emission variations with P_{el}. But η_{el} higher for pure ethanol, FPBO/ethanol blends compared to diesel fuel with improved air–fuel mixing. Stable combustion and 20kW$_{el}$ power achieved with 50/50 % FPBO and ethanol blend (Fig. 25 (d)).

Bioliquids in MGTs do possess challenges, Jerzy T. et al. (2018) [179] provided overview of challenges and proposed systematic solutions to maintain MGT attractiveness making them compatible with diverse bioliquids. They mapped interrelation between general objectives, including efficiency, low emission operation, durability/reliability, and proposed upgrading measures for selected MGT components. Guidelines address impact of each MGT component operation and suggest adaptations for efficient use of bioliquids with less favorable properties compared to those currently used with MGT's. Enagi. II et al. (2019) [180] experimented liquid fuel spray patterns and combustion characteristics in biofuel-designed combustion chamber with 04 injectors (Capacities of injectors; 2.98, 5.95, 8.93, and 11.90 kg/h). Referring to original article [180]; Fig. 2 and Fig. 6 *(c)*, Injector 2 showed stable operation at 0.1–0.5 bar, injector 3 at 0.2–0.6 bar, injector 4 at 0.5–1 bar. Injector 1 was not operational > 0.1 bar. Injector 2 gave best performance with low-medium pressure (CO: 500–900 ppm, NOx: 11–21 ppm). Injector 4 performed well at high pressures (CO: 95 ppm, NOx: 31 ppm). Injector 2 again gave best spray quality at 0.1–0.7 bar range, Injector 4 excelled at 0.8–1 bar. Referring to rriginal article [180]; Fig. 6 *(C)* illustrate relationship between air inlet pressure, CO, and NOx emissions under each tested case.

Thinking of future energy value of biofuels, a critical review on bioliquids and their use in power generation by T. Seljak. Et al., (2020) [181] proposed systematic approach for changing NG based MGT to NH_3 blend system, addressed MGTs' fuel flexibility compared to ICEs, conclusions made on MGTs being better choice for cost-effective and versatility in utilizing bioliquids for power generation. Authors found biofuels combustion, CO, NOx emissions and power output of MGTs has a unique connection, shown in Fig. 26 (a) and (b). The decrease CO with higher power output attributed advancements in MGT technology, allowing elevated TITs, especially beneficial for bioliquids like FPBO and liquefied wood. These bioliquids, featuring high O_2 %, exhibit significantly lower NOx compared to nitrogen-containing waste trap oil. Findings suggests, proper component designs and methods addressing durability issues and high oxygenated bioliquid combined could play a key role in future decentralized power generation with MGT.

Future research trends with MGTs related to biofuels-based combustion and emissions show promising advancements. Researchers increasingly exploring use of biofuels as viable solution in reducing carbon-based fuel use. Studies have been conducted assessing MGT performance using different biofuels, such as biomass-derived synthesis gas and biogas. Indicating biofuels will lead to reduced emissions, and

Table 6
Properties of SVO types, bio-alcohols and biodiesel variants for used with MGT [163–168].

(a) Properties of SVO types used with MGT [165–168]

Fuel	Calorific Value (kJ/kg)	Density (kg/m3)	Viscosity at 25 °C (mm2/s)	Cetane number
Diesel (benchmark)	43.35	815	4.3	47
Sunflower oil	39.525	918	58.5	37.1
Cotton seed oil	39.648	912	50.1	48.1
Soybean oil	39.623	914	65.4	38
Corn oil	37.825	915	46.3	37.6
Opium poppy oil	38.92	921	56.1	–
Rapeseed oil	37.62	914	39.2	37.6

(b) Properties of potential bio-alcohols and biodiesel variants for used with MGT [163–168]

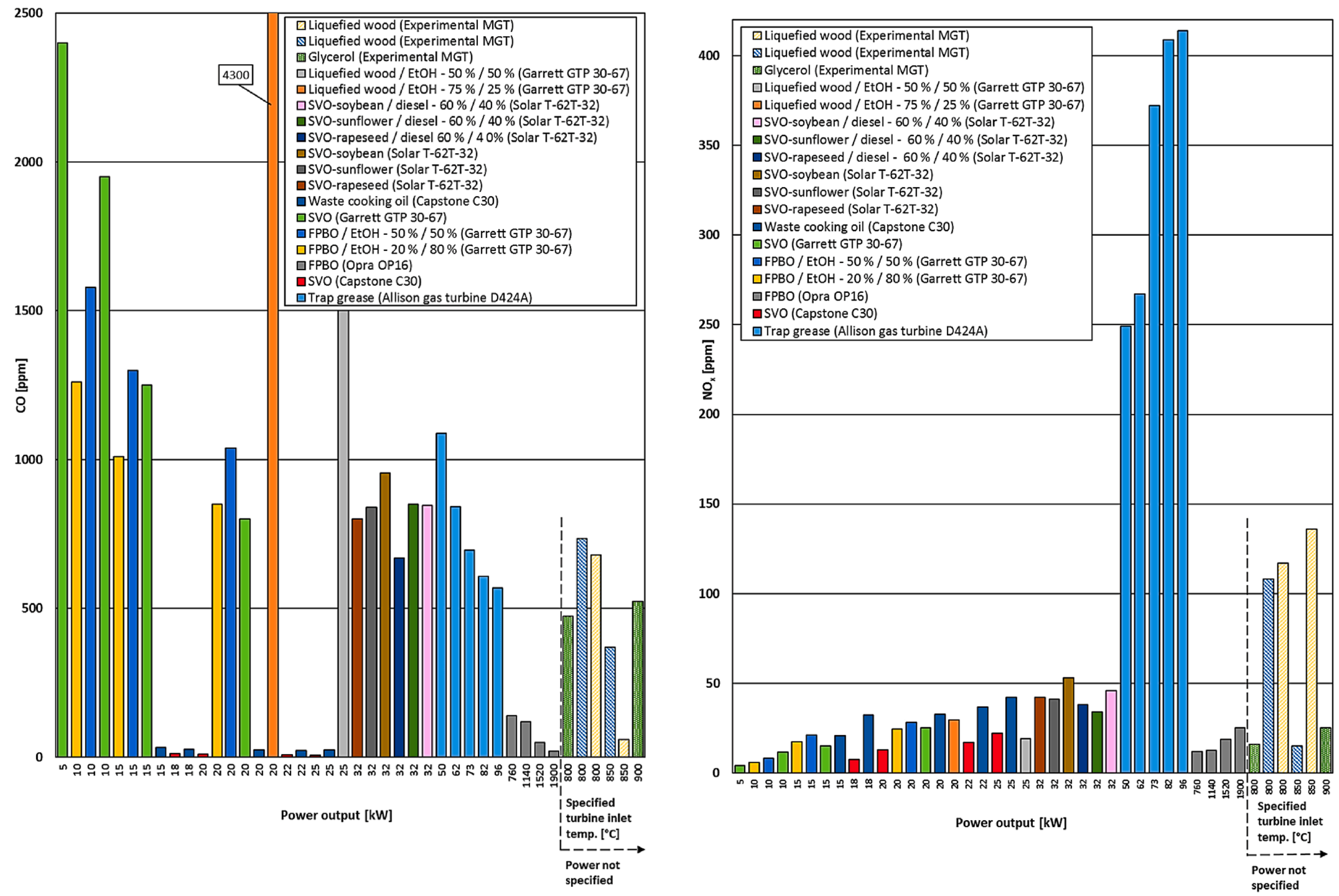
Fuel	Ethanol	Glycerol (crude)	Glycerol (99.5 %)	Biodiesel (Canola oil)
Density (kgdm − 3)	0.817	~1.22	1.26	0.878
Heating value (MJ/kg)	22.8	13.5	16	38.75
Water content (wt. %)	–	11.85	–	–
Viscosity at 40 °C (mm2 s − 1)	1.1	–	230	5
Solubility in FPBO (%)	>95	N/A	<5	<10
Solubility in liquefied wood (%)	<10	N/A	>90	<5

present challenges in terms of efficiency and combustion characteristics. Efforts been made to optimize fuel blends, injection methods, combustor designs to improve MGT performance with biofuels. Integrating MGTs with ORCs and other bottoming cycles shown potential for enhanced power generation using exhaust gases, however, higher CAPEX & OPEX is an serious issue required to minimize via TEA. Additionally, research streams focused on addressing challenges of using bioliquids in MGTs, proposing upgrading measures to ensure compatibility and efficiency. Ultimately, MGTs' future will rely on fuel flexibility. The research area on MGTs "*fuel flexibility*" will experience exponential growth as a widely spread multidisciplinary research segment. Current trend shows NH_3 becoming a cost-effective option for H_2 transportation, making a hot topic for extensive research activities to come. The potential for utilizing biofuels and H_2 will be significant in future decentralized energy market. Biofuels-based MGT, as a multidisciplinary research segment, is expected to experience rapid growth in the future.

2.12. H_2 and NH_3 as fuel for MGT

As a combined summary of sections from 2.6, 2.10 and 2.11, special trends in fuels such as H_2 and NH_3 need special attention with MGTs. H_2 is a clean fuel without carbon emissions, its physical and chemical properties differ significantly from hydrocarbon fuels·NH_3 gas easily decomposes into H_2 gas at high temperatures. The addition of decomposed NH_3 gas could possibly be a single-fuel for MGT operation which could easily replace the hydrocarbon fuels·NH_3 and H_2 as fuels now become a set target for economic feasibility of MGTs. H_2 has 1/3rd of volume energy density of methane (In Table 7), leading to higher volume flow/velocity when providing same amount of heat [155–160]. This raises challenges in adapting combustion systems between H_2 and hydrocarbon fuels. Mixing H_2 with NG weakens swirl stability. New trending research has developed methods to burn H_2-rich fuel or pure H_2 with MGT combustor, but combustion of 100 % H_2 faces challenges with instability and variations in flame morphology [102,107,109]. Researchers have developed several prototype combustors and proposed LES simulation-based methods to handle H_2-rich gas, achieving low CO and NO_x emissions, but H_2 embrittlement and water corrosion remain concerns require solutions with coatings and low H_2 permeability materials [170–173]. Important features of NH_3 with MGT combustion compared with other conventional fuels listed in Table 7(a).

NH_3 considered as a potential H_2 carrier for carbon-free power generation in MGTs, with different combustion characteristics from conventional fuels·NH_3 as a fuel gained much interest due to abounded and availability compared to H_2. New combustion technologies have been researched and several being established for NH_3 application in MGTs, achieving high η_{comb} and reducing emissions [174]. AIST achieved successful NH_3-kerosene-air gas turbine power generation and modified system to NH_3-air combustion. Kurata et al. (2019) [175] modified 50 kW MGT for NH_3-air operation, obtained high η_{comb}. GHGE (CO, NO) directly influenced by combustion chamber inlet temperature, excess NH_3 % recommended to reduce these emissions. Okafor et al., (2021) [176] demonstrated high-efficiency NH_3 combustion chamber technology with reduced NOx emissions. Ayaz et al. (2020) [177] explored NH_3 spray combustion, suggesting co-combustion with methane for better emission performance·NH_3, an additive gas, could decrease CO emissions by 50 %. However, there is no confirmed combustion method accurate enough for these non-conventional two fuel types to be utilized in MGT's in stable & sustainable power generation. Table 7(b) lists several key features of NH_3 and H_2 compared with CH_4. Densities similar with CH_4 and NH_3 but calorific values H_2 and NH_3 has 12.5 % difference. Prominently H_2 as fuel is hazardous with violent laminar flame velocities > 3.5 m/s. Recent literature identifies key NH_3 combustion concerns as low laminar burning velocity and potential for high NOx production. Challenges of using NH_3 as fuel in MGTs involve corrosion, toxicity, but adopting materials like steel, cast iron, and carbon graphite can be used for storage and piping. Monitoring NH_3 concentration is vital for MGTs (MGTs operate in confined spaces/residential areas) as levels above 300 ppm pose immediate risks to human health. Considering NH_3 as a fuel for MGT combustion, it should also need to focus on evaluating energetic and economic indicators of NH_3 and other possible various fuels with their storage, production, and transporting capability. These indicators include specific energy per fuel mass and volume, volumetric chemical exergy for fuel tank potential (carrier), and costs of fuel·NH_3 as a fuel compared with conventional fuels used in MGTs like gasoline, CNG, LPG, methanol, and H_2. Table 8 presents data on fuel type, storage type, fuel pressure, density in the tank, specific fuel energy based on HHV, and volumetric energy is obtained by multiplying HHV with density. H_2 is challenging to store efficiently with its low energy content per unit volume, impacting its driving range and necessitating high power generation efficiency. H_2 production costs vary significantly depending on methods, ranging from $1/kg (coal gasification) to $9.50/kg (solar-driven electrolysis). Storage and distribution costs are substantial with compression or liquefaction requirements, making minimum expected H_2 price around CN$2.5/kg (coal) and CN$11/kg (solar), while DOE goal is $2–3/kg·$NH_3$'s HHV and density are lower than gasoline's, resulting in 2.5x times less energy storage per volume·NH_3 production from fossil fuels involves gasification, CO_2 removal, and catalytic conversion, with efficient synthesis process compensating for energy-intensive components·NH_3 costs per unit of energy vary based on feedstock, ranging from CN$5.25/GJ to CN$20.0/GJ, or CN$0.10 to CN$0.38 per kg. Actual costs worldwide range from $0.15/kg (North Africa) to $0.35/kg (Terra Industries). Cost of energy in the form of NH_3 ~ CN$13.3/GJ, compared to CN$28.2/GJ for CNG, NG is a common feedstock for NH_3 production·NH_3, with an energy density of 18.6 MJ/kg, contrasts with H_2's 120 MJ/kg, making H_2 a favored alternative fuel. However, factoring in losses from heating, cracking, and post-polishing (ammonia removal), cracked hydrogen's energy aligns with original ammonias. If 1 kg of NH_3 is considered, using it as fuel allocates 2 % to SCR operation, yielding approximately 311.4 MJ of energy. Conversely, the same NH_3 amount yields 0.0018 kg of H_2, equaling approximately 2172 MJ of energy, though 15 % powers



(a) (b)

Fig. 26. Relation of (a) CO emissions and (b) NOx emissions to the power output of MGTs operating with biofuels [169–181].

Table 7
Important Characteristics of NH3, H2 and Methene [170–210].

(a) Ammonia (NH_3) features compared with other conventional fuels [170–208]					
	Gasoline	Diesel	Natural Gas	H_2	NH_3
Flammability limit, volumes % in air	1.4–7.6	0.6–5.5	5–15	4–75	16–25
Auto-ignition temperature, °C	300	230	450	571	651
Peak flame temperature, °C	1977	2053	1884	2000	1850
(b) Physical and combustion characteristics of Methene, H2 and NH3 gaseous fuels [170–210]					
Fuel		Density (kg/m3)	Volume calorific value (MJ/m^3)	Ignition temperature (°C)	Laminar flame velocity (m/s)
Methane		0.717	35.6	540	0.38
Hydrogen (H_2)		0.089	12.6	571	3.51
Ammonia (NH_3)		0.771	14.4	651	0.07

cracking, leaving 1846.2 MJ net energy. With similar energy output, capital costs of SCR and cracking units for a daily NH_3 volume need to be considered if NH_3 is used as a fuel for MGTs with time.

Unconventional fuels require extensive examination before introducing commercialized MGTs. Utilization of both 0D and CFD analysis with study of combustion kinetics within MGTs fueled by alternative sources such as Biofuels, NH_3 and H_2 is a necessity. Several studies focused on employing combination of 0D and CFD analyses to gain deeper insights into combustion behavior. For instance, Cappelletti et al. utilized CFD to redesign Turbec T100 combustor chamber for 100 % N_2 fuel, identifying issues with high-temperature ignition. Devriese et al. employed CFD to design 100 kW H_2-fueled MGT, focusing on micromix combustion design. Tuccillo et al. [99] compared the response of lean-premixed and pseudo-RQL combustors increasing H_2/methane blends. Reale et al. compared experimental data with CFD simulations for Turbec T100 using different H_2/methane blends. Meziane et al. conducted 3D-CFD simulations of RQL combustor combustion process varying H_2/CH_4 compositions. Shih et al. studied combustion effects with can-type combustor varying CH_4/H_2 ratios. Calabria et al. examined combustion behavior in Turbec T100 fueled by NH_3 and doped CH_4/H_2 blends at part load. The discussion further extends to biomass-derived gaseous fuels. Such as, Bazzoyar et al. explored biogas MGT combustor behavior using a combination regime with accurate turbulence modeling with RANS and steady diffusion flamelet approach. Ilbas et al. investigated H_2 addition effects to biogas and turbulator angle variations on combustion kinetics to improve temperature distribution. Moreover, adoption of alternative fuels like synthesis gas (Cadorin et al., Calabria et al.) and biogas (Calabria et al.) into Turbec T100 combustor

Table 8
Comparison of NH_3 with other fuels including H_2 with storage, density, energy, exergy, and unit cost comparison [181–222].

Fuel/Storage (Handling) Method	Storage [P] [bar]	ρ Density [kg/m3]	HHV [MJ/kg]	HHV/ Unit Volume [GJ/m3]	Specific exergy/Unit Volume [GJ/m3]	Unit Price [CN$/kg]	Price/Unit volume [CN$/m3]	Unit Price/HHV [CN$/GJ]
Gasoline, C_8H_{18}/ liquid	1	736	46.7	34.4	34.4	1.36	1000	29.1
CNG, CH_4/integrated storage	250	188	42.5	10.4	7.8	1.2	226	28.2
LPG, C_3H_8/ pressurized tank	14	388	48.9	19	11.7	1.41	548	28.8
Methanol, CH_3OH/ liquid	1	786	14.3	11.2	9.6	0.54	421	37.5
Hydrogen, H_2/metal hydrides	14	25	142	3.6	3	4	100	28.2
Ammonia, NH_3/ pressurized tank	10	603	22.5	13.6	11.9	0.3	181	13.3
Ammonia, NH_3/metal amines	1	610	17.1	10.4	8.5	0.3	183	17.5

examined using CFD analysis, to overcome difficulties with experiments with dual-fuel methodology and modifying fuel feeding system, to ensure stable combustion anomalies and strategies stabilizing MGT operation. The literature review is summarized version [45–216] in Appendix C. Discussed throughout this paper, many modern micro-scale power generations combined with MGTs, focus on reducing GHGE and transitioning to renewable and non-carbon energy sources are paramount. Researchers aim to expedite the transition from current energy systems to greener alternatives. Concurrently, research targets short- to medium-term solutions, such as DEGS and small-scale smart grids, being viable solutions for emission reduction through CHP. MGTs < 500 kW range offer flexibility, catering various fuels, loads, and CHP/CCHP applications. Pas decades saw efforts with small-scale energy systems based on MGTs, but recent research streams strongly emphasize alternative/un-conventional fuels (biogas, syngas, H_2, NH_3 etc.), performance enhancement strategies, integration into complex hybrid energy landscapes to meet sustainability goals. MGT based diverse research categories tend to explore flexibility, though limited electrical efficiency persists. To achieve these targets, numerical modeling has been used extensively, complementing experimental data with validation, and providing useful insights. Appendix B provides extended case studies on recent MGT advancements in numerical modeling, investigating energy-efficient plant layouts, covering innovative thermodynamic cycles, hybrid systems, CFD analysis, and explicitly highlight the analyzed feature on MGT system [27–222].

3. Discussion and conclusions

The growing use of MGTs led to combinations of more complex systems like CSP, SOFC, Wind and PV, grid-connected, and grid-independent generation. Regulation of MGTs under multi-factor operating conditions becomes a common concern. Energy injection varies among different systems, network of MGT related system landscape has a broad applicability. A generalized system model and regulation mechanism, based on the energy supply black box approach, would be beneficial for adapting MGTs to diverse systems towards a sustainable future. Referring to Fig. 27, multidisciplinary research activities on MGT have increased readily for last two decades in every major multidisciplinary area and showed considerable progress and promise as a reliable future power generation mode. Several research areas demonstrated rapid growth, potential for future development, while others face challenges and limitations.

1. CSP with MGTs shows potential for efficient power generation but hindered by high initial costs, intermittent solar energy, and efficiency losses. This research area has limited prospects in future due to competition from more affordable and less complex MGT-based power generation systems.
2. MGT-based CGS and TGS hold promise for sustainable energy solutions. Ongoing research in this field focuses on various aspects such as optimization, integration with renewables, and

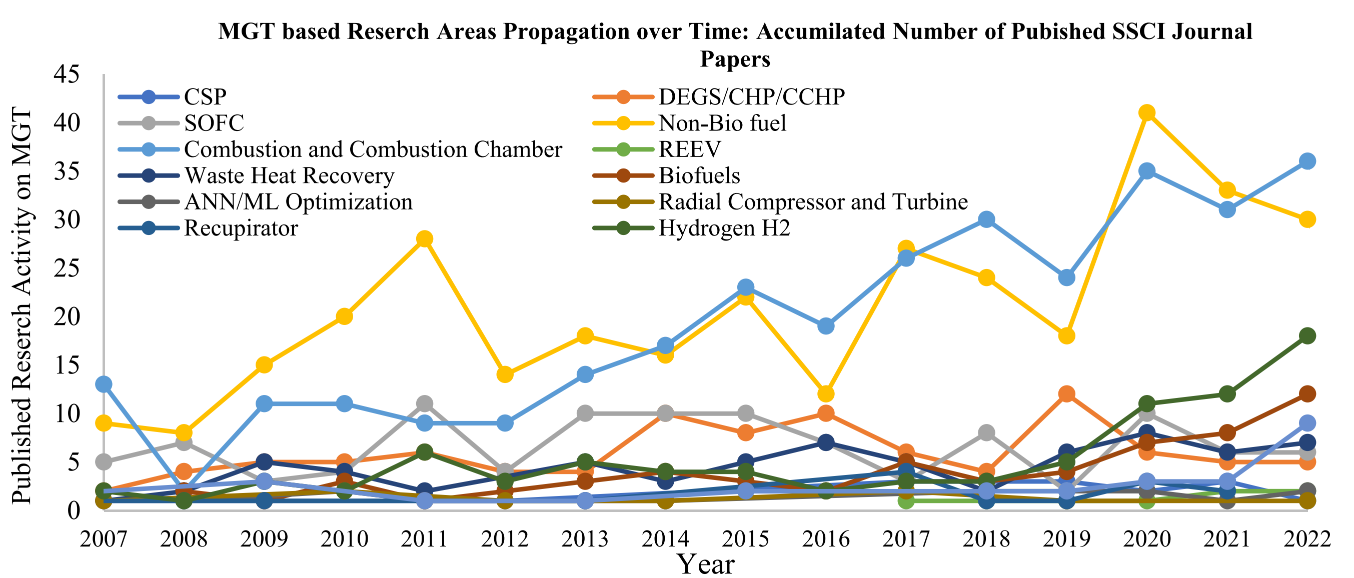


Fig. 27. MGT based multidisciplinary research fields progress and trends over time.

innovative load management. CCHP and MGT-based research aligning with cooling systems are key areas for future exploration.

3. Advancements in MGT technologies and efficient WHR cycles in future trends will focus on integration of WHR cycles, such as SE and ORC, with MGTs promising for enhancing overall η_{th} and sustainability in co-production systems. Despite initial cost challenges, long-term benefits are compelling. WHR systems lead to higher efficiency, reduced emissions, improved energy security, and energy "Trilemma" fulfillment. Upfront investment may be higher, potential fuel savings, heat and electricity revenue, future cost reductions make proposition economically viable. Supportive policies, incentives, and a comprehensive lifecycle cost analysis further strengthen justification for MGTs with WHR, positioning a valuable solution for meeting energy and environmental goals in providing practical solutions to mitigate climate change.
4. High-precision simulation and intelligent optimization segment will progress utilizing CFD for accurate aero-thermal dynamic and heat transfer analysis, along with A.I methods (GA, ANN) for design and optimization, with emphasis on digital twin technology for dynamic component interactions and health monitoring. Integration of ANN/ML with MGTs shows exponential growth while optimizing, enhancing MGT performance, emissions reduction, and predictive maintenance planning negating human errors.
5. MGT with REEV's are advantages for electrifying the future of automobile sector, challenges remain, particularly in competing with mature battery and FC technologies.
6. MGT-based Combustion Kinetics and CC applications have made progress in improving efficiency and reducing emissions. Upcoming trend be adaptive combustion technology to reduce emissions and broaden the use of sustainable fuels, exploring flameless combustion (FLOX) and generic combustion structures for cost-effective fuel switching. Research will focus on stability issues with low-calorific-value fuels and NOx emissions with H_2-rich syngas.
7. MGT-based radial type compressor and turbine applications have made significant progress in the past, but further advancements may be slow due to approaching peak efficiencies.
8. MGT-based recuperators focus on low-cost fabrication and optimization methods. Future progress will look for efficient heat exchangers to reduce investment costs and flow losses. Focusing on primary surface and microchannel heat exchangers, additive approaches, and bionic technologies to improve heat transfer capacity and material properties, being hot topics. This field may have slower growth as thermal efficiencies are already high.
9. Integration of SOFC with MGT in hybrid systems shows great promise in terms of high efficiency and environmental friendliness. Ongoing research will further enhance overall efficiency and reduce costs.
10. MGT-based research on alternative fuels for reducing emissions show promise in reducing environmental impact and increasing overall efficiency. Fossil fuel-based research activities are declining, and the future lies only in the path of optimizing combustion systems for alternative fuels and combustion methods.
11. Biofuels-based MGT research shows promising advancements in reducing carbon-based fuel emissions. Research efforts will focus on fuel flexibility, utilization of biofuels, and the potential of NH_3 and H_2 as cost-effective methods for future energy applications.
12. NH_3 and H_2 usage as fuel-based research in MGTs has the highest potential and it this trend will be the future leading pathway for MGTs in the future landscape of carbon neutral power generation. Both NH_3 and H_2 are poised to contribute towards net zero strategies. While further technological development could make NH_3 a more economical fuel choice than acting as a H_2 carrier, the decision should be based on the maturity and sizing of NH_3-based turbines, and fuel cells compared to, H_2 engines, and fuel cells for each specific application.

Overall, MGT-based multidisciplinary research is diverse, with some areas balanced for rapid growth and others requiring continuous efforts to overcome challenges. This paper provides a comprehensive and detailed review of MGTs, discussing commercial developments, applications, performances, and latest research on components. To enhance MGT performance and applications, this review study emphasizes several key areas for future research activities such as prototyping and/or testing hot end components and thermal protection, adaptive combustion technology, high-precision simulation (LES) and intelligent optimization using ANN and AI based, high-efficiency and low-cost heat exchange technology, efficient WHR cycles specially trigeneration to cater upcoming cooling demand due to global temperature rise and intelligent control technology. These advancements are essential for increasing thermal efficiency, reducing emissions, and expanding adaptability of MGTs in various energy systems. But future progress of MGT technology lies predominantly in improvements of fuel flexibility, usage of alternative fuels, with close inspection in Fig. 27, advancements, and trend specially for Biofuels, NH_3 and H_2 is rising in recent years and keep on improving while all most all other sub disciplines showing declining trends with research activities with MGTs. Developments of innovative combustion techniques to achieve cleaner and more efficient power generation modes with reduced environmental impact will be economically viable for MGTs in future progress. A spike of research activities bloomed in fossil fuel-related combustion-based research during 2020. This period can be the pinnacle of MGT based multidisciplinary advancements and activities on shifting tracks from conventional fuels to almost 100 % non-conventional fuels-based research streams. But this occurrence can be interpreted as the final effort or cumulative effort on research activities which has taken by the researchers who worked on conventional fuels-based combustion and emission multidisciplinary area on trying to extract the maximum exergy by optimizing the classical fossil fuel-based systems. from that point onwards, the clear decline of conventional fuels-based research category has shifted its tracks and turned to H_2 and NH_3 based combustion systems with design and optimization, searching new ways to power up MGTs with H_2 and NH_3 choosing as environmentally friendly and sustainable fuel sources for the long run to come. With past two decades of progress when analyzed in detailed manner, these identified contemporary trends paradigm shift on MGTs are highly unlikely to change for the next two decades to come.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: A. H Samitha Weerakooon reports financial support was provided by Horizon 2020 European Innovation Council Fast Track to Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Flexibility.

Appendix A:. Summery of previous MGT review papers: Findings and gaps

Previous MGT Review Studies Study	Authors/Year/Journal Publisher	Purpose and the Scope of Review
Externally fired gas turbine technology: A review [13]	K.A. Al-attab et al., (2014)/ Applied Energy, Volume 138, 15 January 2015, Pages 474–487	Various thermal power sources that can be used with EFGTs, including concentrated solar power, fossil fuels, nuclear energy, and biomass. It also examines the dissimilar materials and designs of high-temperature heat exchangers (HTHE) and explores methods to improve cycle efficiency, such as externally fired combined cycles, humidified air turbines, EFGTs with fuel cells, and other innovative cycles. Overall, the focus is on the potential and versatility of EFGTs for a wide range of power generation applications.
Study on the Parameters Influencing Efficiency of Micro-Gas Turbines: A Review [14]	Samarth Jain et al, (2015) /ASME 2015 Power Conference, June 28–July 2, 2015, San Diego, California, USA	A review on developments in MGTs and address challenges with components, such as the recuperator and combustion chamber design. Additionally, it explores the prospects of MGTs in the automobile sector. including safety issues related to elevated temperature levels, sensitivity to ambient temperature, and cost-effectiveness in terms of initial investment and maintenance. Development of micro fluid machinery compatible with current fabrication technology. Achieving high system efficiency and exploring applications such as portable systems, aerial vehicles, and hybrid-electric vehicles.
Towards Higher Micro Gas Turbine Efficiency and Flexibility: Humidified MGTS — A Review [15]	De Paepe. W et al, (2017)/ ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition, June 26–30, 2017, North Carolina, USA	Discuss humidified-MGT cycles and highlight the advantages and disadvantages of different humidification options, including their economic potential. The mHAT technology, which introduces water in the cycle using a saturation tower with water recovery loop, is identified as the most promising option based on thermodynamic and economic analysis. Also highlights the limitations to the commercial development of humidified cycles, including recuperator degradation, control strategy, and regulatory constraints.
Recuperators for micro gas turbines: A review [16]	G. Xiao et al., (2017) / Applied Energy 197 (2017) 83–99	The recuperators work task in MGTs. Discuss topics such as primary-surface recuperators are preferred over plate-fin and tubular ones, and ceramic recuperators outperform metallic ones at elevated temperatures. Heat transfer and pressure for designing effective recuperators, requirement of further experimental and simulation studies to develop accurate empirical correlations. Optimization methods, especially multi-objective approaches, to balance pressure loss, heat transfer effectiveness, compactness, and cost. Research on manufacturing techniques like 3D printing and printed circuit heat exchangers to further enhance recuperator development.
Effects of Fuel and Nozzle Characteristics on Micro Gas Turbine System: A Review [17]	Muhammad A.H et al., (2017)/IOP Conf. Series: Materials Science and Engineering 226 (2017)/ 012,006	The combustion performance of a MGT using a dual-fuel nozzle, specifically focusing on the use of biogas as a clean fuel alternative. Paper discusses the modeling of the nozzle characteristics and investigates the effects of using biogas as a substitute for methane in terms of flame temperature and fuel flow rate.
Review: Advances in Biofueling of Micro Gas Turbines for Power Generation [18]	Edmund C. Okoroigwe et al., (2018)/ Energy Technlogy Volume7, Issue5 May 2019/ 1,800,689	Focuses on the integration of biofuels into MGT systems for power generation. Addressing the obstacles limiting the deployment of biofueled MGTs for commercial power generation, including the properties of biofuels and their combustion characteristics, higher cost compared to conventional fuels. Other concerns include food security, land use, feedstock types, and cultivation practices.
Enhanced life cycle modelling of a micro gas turbine fueled with various fuels for sustainable electricity production [19]	S.Kagan Ayaz et al, (2021)/ Renewable and Sustainable Energy Reviews 149 (2021) 111323.	This review discusses the exergy and life cycle-based enhanced environmental (EXEN) and enviro-economic (EXENEC) analyses on a MGT operated with different fuel mixtures (natural gas, natural gas-ammonia, and natural gas-methanol). The study identified limitations, such as the ammonia production methods and emissions prediction in the burner, why ammonia had a higher CO reduction compared to methanol. And discuss methods to reduce greenhouse gas (GHG) emissions.
Micro Gas Turbines in the Future Smart Energy System: Fleet Monitoring, Diagnostics, and System Level Requirements- Review [20]	Ioanna A. et al., (2021)/ REVIEW article Mech. Eng., 01 June 2021 Sec. Engine and Automotive Engineering. Volume 7——2021	The use of an engine monitoring and diagnostics system to improve the reliability of MGTs used in domestic applications. Methods of fleetwide monitoring and diagnostics, purpose-designed systems to compare data from different engines. A simplified “mother” engine model to assist in real-time diagnostics for the entire fleet, reducing maintenance costs. Maintaining a

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Previous MGT Review Studies Study	Authors/Year/Journal Publisher	Purpose and the Scope of Review
		framework for decision support diagnostics to include optimal operation and production planning.
The Role of Micro Gas Turbines in Energy Transition- Review [21]	Reyhaneh Banihabib (2022)/ MDPI Jounral: Energies 2022, 15(21), 8084.	Investigates the role of MGTs in the energy transition and highlights their potential as dispatchable standby units in renewable-dominant power generation. Challenges and areas for improvement are discussed, and an active monitoring and control system utilizing AI techniques is proposed to enhance reliability. Discuss how AI-based tools can optimize operational strategies, increase efficiency, and improve investment returns. Why digitalization and real-time analysis are essential for maximizing the benefits of MGTs in existing installations.
Numerical Modeling of Energy Systems Based on Micro Gas Turbine: A Review [22]	Reale F. et al., (2022)/ MDPI Journal: Energies 2022, 15(3), 900: Special Issue: Energy Systems and Fluid Machinery 2022	Review discusses the importance of numerical modeling in analyzing and predicting the behavior of MGT-based energy systems and discusses different modeling approaches, methods numerical tools for modeling MGT systems employed in recent MGT based research work.
Micro Gas Turbine Role in Distributed Generation with Renewable Energy Sources- Review [23]	Roberta De R. et al., (2023) / MDPI Energies Journal: 2023. Special Issue: Combustion in Reciprocating Engines or Gas Turbines	The review explores the use of MGTs in distributed generation systems (DEG) and their integration with various technologies and their performance both individually and in micro-grid configurations and tried to provide an understanding of the potential of MGTs in achieving sustainable energy generation.
ReviewMicro gas turbine: Developments, applications, and key technologies on components [24]	Jingqi Li., Propulsion and Power Research, Volume 12, Issue 1, March 2023, Pages 1–43	MGTs and their applications in various energy systems. Highlights the development status, applications, performance factors, and representative explorations of MGT components. Various technologies and approaches have been employed in the design and production of MGTs and their components. The review provides distinct introductions to these applications and investigates the characteristics of commercial MGTs.
Improving efficiency of MGT systems by integration of combustor and recuperator using additive manufacturing techniques- A critical Review [25]	Sheykhpoor, H. et al., (2023). The International Journal of Advanced Manufacturing Technology, 11 May 2023.	Focused on additive manufacturing (AM) of MGTs on component level. The use of AM, particularly in the hot section of the gas turbine, such as the combustor and recuperator. Discuss how this type of AM method would lead to higher efficiency and reduced weight and volume of MGT units.
Dynamic performance and control strategies of micro gas turbines: State-of-the-art review, methods, and technologies [26]	M. Baqir Hashmi et al., (2023)/ Energy Conversion and Management: X 18 (2023) 100,376	Review compares various control methods, including conventional, optimized, and artificial intelligence-based controllers, to identify robust controllers for future applications. It also highlights the scarcity of literature on the transient performance of MGTs using alternative fuels such as hydrogen, methanol, ammonia, syngas, and biomethane. Addresses the challenges associated with alternative fuels in MGTs and provides recommendations for reliable MGT operation during transient conditions.

Appendix B:. Case studies of MGTs reviewed with analysis feature. [27–187]

	MGT Model	Numerical tool/software method	Feature analyzed	Reference
Solar-MGT Hybrid Systems	25 kW MGT	MATLAB + In-house (Axtur)	Solar assisted recuperated MGT with receiver and internal combustor	Wang,W. et al. Energy Procedia 2015, 69, 583–592
	Turbec T100	Aspen Plus	Single recuperator-based system based on solar and biomass	Kautz, M. et al. Appl. Energy 2007, 84, 795–805
	5 kW	Ansys Fluent	Dish type-MGT modeling and validation	Giovannelli, A. et al. Energy Procedia 2017, 126, 557–564
	Compower	MATLAB	Solar receiver performance on MGT (pressurized and ambient configurations)	Aichmayer, L. et al. Sol. Energy 2015, 114, 378–396
	Capstone C30	Thermoflex/Ansys Fluent	Solar assisted heating capacity/ Scaling effect on Internal combustor	Cameretti, M.C. et al. Energy Procedia 2015, 82, 833–840
	80 kW	In-house (DYESOPT)	Array system of dish type-MGT copuled with ST	Aichmayer, L. et al. Energy Procedia 2015, 69, 1089–1099
	10 kW MGT	MATLAB/Simulink	Solar assisted MGT performance evaluation with TCES	Yang, J. et al J. Clean. Prod. 2021, 304, 127,010
	100–200 kW	MATLAB	Solar-governed, recuperated MGT + auxiliary heater performance	Giostri, A. et al. Energy 2020, 147, 570–583, Giostri, A. et al. Sol. Energy 2016, 139, 337–354
General Recuperated MGT Units	Capstone C65	Modelica	Black box	Gopisetty, S et al. Energies 2017
	Capstone C30	Mathcad	Part-load correlation	Malinowski, L. et al. Appl. Therm. Eng. 2013, 57, 125–132
	Turbec T100	IPSEpro	Steady-state thermodynamic with compressor and turbine characteristic maps	Nikpey Somehsaraei et al. Appl. Therm. Eng. 2014, 66, 181–190

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	MGT Model	Numerical tool/software method	Feature analyzed	Reference
	20 kW MGT	Matlab/Simulink	Dynamic	Cáceres, C.X. et al. Int. J. Hydrog. Energy 2012, 37, 10111–10117
	Turbec T100	Matlab/Simulink	quasi-stationary components and static maps	Caresana, F. et al. Appl. Energy 2014, 124, 17–27
	Capstone C30	–	Numerical methodology validation	Gimelli, A. et al. Appl. Therm. Eng. 2018, 134, 501–512, Gimelli, A. et al. Energy Procedia 2017, 126, 955–962
	Turbec T100	–	Numerical methodology validation	Gimelli, A. et al. Energy Procedia 2018, 148, 2–9, Duan, J et al. Energy 2015, 91, 168–175
	Capstone C30	GT-SUITE	1D simulation of Radial Turbine and Compressor	Gimelli, A. et al. Appl. Therm. Eng. 2021, 188, 116,644
	Capstone C30	Matlab/Simulink	Dynamic non-linear modeling and simulation	Zornek, T. et al. Appl. Energy 2015, 159, 276–284
	Turbec T100	Matlab/Simulink	Low LHV combustion kinetics and performance	Panne, T. et al. 5th International Energy Conversion Engineering Conference and Exhibit (IECEC), USA, 25–27 June 2007. Paper No. 2007–4833
	Turbec T100	Matlab/Simulink	Component maps, simulation of the T100 control algorithms	Henke, M. et al. J. Eng. Gas Turb. Power 2013, 135, 091203, Henke, M. et al.ASME Turbo Expo 2015, C, Canada, 15–19 June 2015. Paper No. GT2015-42090
	3 kW Turbocharger	GSP	Cycle modeling for different component efficiencies and losses	Visser,W.P.J. et al. J. Eng. Gas Turbine Power 2011, 133, 042,301
	3 kW Turbocharger	GSP	1D recuperator analysis	Visser, W.P.J. et al. ASME Turbo Expo 2015, Canada, 15–19 June 2015. Paper No. GT2015-42744
	Turbec T100	In-house developed code/Matlab	Steady-state—0D model with compressor and turbine characteristic maps/ Dynamic first-order ODE	Di Gaeta, A. et al. Energy 2017, 129, 299–320
MGT-SOFC Hybrid Systems	50 kW	MATLAB	Turbine and Compressor performance maps	Costamagna, P. et al. J. Power Sources 2001, 96, 352–368
	3 kW	In-house (MGTS3—Micro Gas Turbine Steady State Simulator, MATLAB/Simulink based)	Turbine and Compressor performance maps	Krummrein, T. et al. Appl. Energy 2018, 232, 598–606
	5 kW	MATLAB/Simulink	Dynamic behavior of MGT	Kaneko, T. et al. J. Power Sources 2006, 160, 316–325
	Theoretical	In-house (Dynamic Network Analysis)	Comparison of Thermodynamic model with commercial MGT model	Bang-Møller, C. et al. Energy Convers. Manag. 2010, 51, 2330–2339, Bang-Møller, C. et al. Energy 2011, 36, 4740–4752
	Conceptual Model	Engineering Equation Solver	Energy, Exergy and Mass balance	Ebrahimi, M. et al. Energy Convers. Manag. 2016, 116, 120–133
	Not Specified	Aspen Plus	Un-specified	Zhao, H. et al. Energy 2019, 44, 4332–4349
	Turbec T100	ChemCAD	TIT variability with SOFC (Subroutines for SOFC and gasifier)	Di Carlo, A. et al. Energy 2013, 38, 5857–5874
	50 kW	In-house (TRANSEO, MATLAB/ Simulink based)	Analyzing transient behavior of MGT	Ferrari, M.L. et al. J. Power Sources 2005, 149, 22–32
	Not Specified	N.A.	Modeling of system using 0D and 1D method	Wongchanapai, S. et al. J. Power Sources 2013, 223, 9–17
	Turbec T100	Aspen Plus	Not specific	Perna, A. et al. Appl. Energy 2018, 227, 80–91
	Capstone C30 and C60, Parallon 75 kW, Turbec T100	Aspen Plus	Alternative operational pathways for Turbine and Compressor with combustor performance	Bakalis, D.P. et al. Appl. Energy 2013, 103, 607–617
	Conceptual Model	Aspen Plus	Conceptual thermodynamic model with varying efficiencies	Fryda, L. et al. Energy Convers. Manag. 2008, 49, 281–290
MGT-ORC Hybrid Systems	Capstone C600s	Commercial Code AmeSIM	Turbine and Compressor performance maps generation	Baccioli, A. et al. Appl. Energy 2019, 256, 113,960
	Turbec T100	Thermoflexa and Ansys CFX	Performance maps generation/ Turbulence modeling: RANS RSM	Reale, F. et al. ASME Turbo Expo 2020, Online. 21–25 September 2020. Paper No: GT2020-15401
	Turbec T100	Aspen Plus	Development of Performance maps	Moradi, R. et al. Energy Convers. Manag. 2020, 205, 112,464
	Conseptutal Model	EES-based Model	Mass and energy balance and comparison with Reference model	Nazari, N. et al. Appl. Therm. Eng. 2020, 179, 115,521
	Turbec T100	Matlab/Simulink	Mass and energy balance, Component performance maps	Xiao, G. et al. Energy Convers. Manag. 2021, 243, 114,032
	Turbec T100	Thermoflex/Ansys Fluent	Component performance maps/Step wise oxidation performance within a defined rate—eddy disperse model	Cameretti, M.C. et al. ASME Turbo Expo 2015, Canada, 15–19 June 2015. Paper No. GT2015-42572
	Conseptutal Model	EES-based	Energy conversion calculation/Mass and energy balance	Nazari, N. et al. Appl. Therm. Eng. 2021, 191, 116,889
	Conseptutal Model	EES	Genetic Algorithm (GA) based multi-objective optimization	Chacartegui, R. et al. Energy Convers. Manag. 2015, 104, 115–126
Externally fired MGT Systems	100 kW MGT	In-house developed code	Mono-recuperator performance	Datta, A. et al. Energy 2010, 35, 341–350
	Turbec T100	In-house developed code (AMOS)	Fuel flexibility and Dual fuel capability	Riccio, G. et al. Biomass Bioenergy 2009, 33, 1520–1531
	Turbec T100	Gate-Cycle Code	Fuel flexibility and Dual fuel, NG and Biomass suitability	Pantaleo, A.M. et al. Energy Convers. Manag. 2013, 75, 202–213

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	MGT Model	Numerical tool/software method	Feature analyzed	Reference
	Elliott TA-80R	In-house code (TEMP, TRANSEO)	Dual-recuperator and system level valves position adjustment for cycle control	Traverso, A. et al. Appl. Therm. Eng. 2006, 26, 1935–1941, Magistri, L. Hybrid systems for distributed generation. Ph.D. Thesis, University of Genoa, Genoa, Italy, 2003
Dry and Wet Operation of MGT Systems	Turbec T100	Aspen Plus	Generating performance map for off desing - Compressor and Turbine	De Paepe, W. et al. Appl. Energy 2017, 207, 218–229
	Turbec T100	Aspen Plus	Turbine and Compressor efficiency calculation with thermotical correlations	De Paepe, W. et al. Appl. Energy 2012, 97, 569–576
	Turbec T100	Aspen Plus	Generating Compressor and Turbine maps (Design point and off-design)	Montero Carrero, M. et al. Appl. Energy 2017, 204, 1163–1171
	Conceptual Model	gPROMS/GateCycle	Multiflash database, Advanced Redlich-Kwong-Soave equation of state	Wan, K. et al. Energy Convers. Manag. 2010, 51, 2127–2133
	Turbec T100	Thermoflex/Ansys CFX	Analyzing component performance maps, Turbulence type: RANS/RSM	Reale, F. et al. Int. J. Hydrog. Energy 2021, 46, 24366–24381
	Turbec T100	Aspen Hysys	Thermodynamic modelling of the combustion kinetics and utilizing total Gibbs energy theory	Ali, U. et al. ASME Turbo Expo 2015, Canada, 15–19 June 2015. Paper No. GT2015-42688
	Turbec T100	Aspen Plus	Generating performance map for Compressor and chocked Turbine	De Paepe,W. et al. Appl. Energy 2020, 279, 115,898
	100 and 500 kW	In-house (TEMP, SAT, TRANSEO)	Generating Compressor and Turbine maps	Parente, J. et al. ASME Turbo Expo 2003, USA, 16–19 June 2003; pp. 221–229, Paper No. GT2003-38326, Parente, J. et al. ASME Turbo Expo 2003, Atlanta, GA, USA, 16–19 June 2003. Paper No. GT2003-38328

Appendix C: Numerical analysis case studies on MGT powered by unconventional fuels [188–222]

MGT/ Type of Combustor	Numerical Software	Turbulence Model	Fuel Type	Reference
Turbec T100	Ansys CFX	RANS RSM	NG, H_2/CH_4, Biogas	Calabria, R. et al. ASME Turbo Expo 2015, Montreal, QC, Canada, 15–19 June 2015. Paper No. GT2015-43455
77Turbec T100	Ansys Fluent	RANS realizable k-Ω	H_2	Devriese, C. et al. ASME Turbo Expo 2020, Online. 21–25 September 2020. Paper No. GT2020-14473
Turbec T100	Ansys CFX	RANS RSM	Biogas	Calabria, R. et al. ASME Turbo Expo 2019, Phoenix, AZ, USA, 17–21 June 2019. Paper No. GT2019-91483
Turbec T100	Ansys CFX	RANS k-Ω	H_2/CH_4	Reale, F. et al. Appl. Mech. Mater. 2012, 232, 792–796
RQL Can type	Ansys Fluent	RANS k-ε	H_2/CH_4	Meziane, S. et al. Int. J. Hydrog. Energy 2019, 44, 15610–15621
Turbec T100	Ansys Fluent	RANS k-ε SST	H_2	Cappelletti, A. et al. Energy Procedia 2014, 45, 1412–1421
Turbec T100	Ansys CFX	RANS RSM	NH_3, H_2/CH_4	Calabria, R. et al. ASME Turbo Expo 2014, Düsseldorf, Germany, 16–20 June 2014. Paper No. GT2014-26631
Derived by Bladon MT	–	RANS k-ε SST	Biogas	Bazooyar, B. et al. Fuel 2021, 294, 120,535
Tubular	Ansys Fluent	RANS k-Ω	H_2/biogas	Ilbas, M. et al. Int. J. Hydrog. Energy 2017, 42, 25735–25743
Turbec T100	Ansys CFX	RANS RSM	NG, syngas	Cadorin, M. et al. J. Eng. Gas Turbines Power 2012, 134, 071,401
Turbec T100	Ansys Fluent	RANS realizable k-Ω /DES	H_2/CH_4	Tuccillo, R. et al. ASME Turbo Expo 2019, Phoenix, AZ, USA, 17–21 June 2019. Paper No. GT2019-90229
Can type	Star CCM+	RANS k-Ω	H_2/CH_4	Shih, H.Y. et al. Int. J. Hydrog. Energy 2014, 39, 15013–15115

Appendix D: Studies addressing biofuels in MGTs [188–222].

Title	Year	Turbine engine	Fuel type
Preliminary test on combustion of wood derived fast pyrolysis oil in a gas turbine combustor	2000	Not specified	Wood (eucalyptus) Derived fast pyrolysis oil mixed with ethanol, JP-4.
Biodiesel Air blast Atomization Optimization for Reducing Pollutant Emission in Small Scale Gas Turbine Engines	2007	Capstone C30	Diesel fuel, Biodiesel (from soybean production), Pure ethanol (E100).
Combustion of waste trap grease oil in gas turbine generator	2010	Allison gas turbine - D424A	Diesel, Waste trap grease oil.
Performance and emission characteristics of biofuel in a small-scale gas turbine engine	2010	30 kW gas turbine engine	Soy and canola biodiesel, recycled rapeseed biofuel and their 50 % blends with Jet-A fuel, 50 % blend with hog fat biofuel.
Straight vegetable oil use in Micro-Gas Turbines: System adaptation and testing	2012	Capstone C30	Diesel fuel, Straight vegetable oil and their blends.
Hydro processed Renewable Jet Fuel Evaluation, Performance, and Emissions in a T63 Turbine Engine	2012	T63-A-700 Allison	Hydro processed renewable jet (HRJ) fuel and blends 50 %/50 % with JP-8,
Wood, liquefied in polyhydroxy alcohols as a fuel for gas turbines	2012	Experimental MGT	Liquefied wood, Diesel fuel
Exhaust emissions from liquid fuel micro gas turbine fed with diesel oil, biodiesel, and vegetable oil	2013	Garrett GTP 30–67	Diesel no. 2, Biodiesel, Vegetable oil, Biodiesel/Vegetable Oil Blend.
Alternative feedstock for the biodiesel and energy production: The OVEST project	2013	Capstone C30	Treated waste cooking oil.

(*continued on next page*)

(*continued*)

Title	Year	Turbine engine	Fuel type
Experimental analysis of a micro gas turbine fueled with vegetable oils from energy crops	2014	Solar T-62 T-32	Straight vegetable oil: Rapeseed, Sunflower, Soybean in various blends with diesel.
Quantification of aldehydes emissions from alternative and renewable aviation fuels using MGT	2014	Artouste MK113 APU	Jet-A1, two HEFA, FAE (Fatty Acids Ethyl Ester), GTL (Gas to Liquid).
MGT combustion and emission characterization of waste polymer-derived fuels	2014	Experimental MGT	Liquefied wood, Tire pyrolysis oil, Mixture of glycols, Diesel fuel
The impact of spray quality on the combustion of a viscous biofuel in MGT	2014	DG4M-1	Diesel no. 2, Vegetable Oil
Pyrolysis oil utilization in 50 kWe MGT	2015	DG4M-1	Pyrolysis oil-diesel fuel mixtures, and diesel as reference fuel.
Advanced fuels for GTs: Fuel system corrosion, hot path deposit formation and emissions	2016	Experimental MGT	Liquefied wood, Tire pyrolysis oil
Spray atomization of bio-oil/ethanol blends with externally mixed nozzles	2016	Twin fluid externally mixed nozzles	Bio-oil, Bio-oil blends with ethanol (20:80, 40:60 = Bio-oil:EtOH), ethanol and diesel.
Evaluating high volume blends of vegetable oil in micro-gas turbine engines	2017	Model jet engine, Sr-30	ULSD Diesel, Vegetable Oil (soybean).
Emission reduction through highly oxygenated viscous biofuels: Use of glycerol in an MGT	2018	Experimental MGT	Technical grade glycerol, Diesel fuel
Performance and emissions of liquefied wood as fuel for a small-scale MGT	2019	Garret GTP 30–67	Biomass pyrolysis oil/Ethanol blends
Combustion of fast pyrolysis bio-oil and blends in an MGT	2020	Garret GTP 30–67	Liquefied wood/Ethanol blends
Straight vegetable oil use in MGT: Experimental analysis	2021	Capstone-C30	Diesel fuel, Straight vegetable oil and their blends.

References

[1] "The History of the Gas Turbine | Rochem", rochem-fyrewash.com, (Accessed 22 Jun. 2023).
[2] R. Capata and M. Saracchini. "Experimental Campaign Tests on Ultra Micro Gas Turbines, Fuel Supply Comparison and Optimization", March, 2018.
[3] Mottola F, Proto D, Varilone P, Verde P. Planning of distributed energy storage systems in micro grids accounting for voltage dips. Energies Jan. 2020;13(2):401. https://doi.org/10.3390/en13020401.
[4] S. Gopisetty and P. Treffinger. "Generic Combined Heat and Power (CHP) Model for the Concept Phase of Energy Planning Process". Dec. 2016.
[5] Rahman M, Zaccaria V, Zhao X, Kyprianidis K. Diagnostics-oriented modelling of micro gas turbines for fleet monitoring and maintenance optimization. Processes Nov. 2018;6(11):216. https://doi.org/10.3390/pr6110216.
[6] "POWER TO GAS: HYDROGEN FOR POWER GENERATION", ge.com, (Accessed 22 Jun. 2023).
[7] "Distributed Generation of Electricity and its Environmental Impacts ...", epa.gov, (Accessed 22 Jun. 2023).
[8] "Renewable Energy - Our World in Data", ourworldindata.org, (Accessed 22 Jun. 2023).
[9] Akhtar I, Kirmani S, Suhail M, Jameel M. Advanced Fuzzy-Based Smart Energy Auditing Scheme for Smart Building Environment With Solar Integrated Systems. IEEE Access Jan. 2021;9:97718–28. https://doi.org/10.1109/access.2021.3095413.
[10] N. Mohammad, W. W. M. Ishak, S. I. Mustapa and B. V. Ayodele. "Natural Gas as a Key Alternative Energy Source in Sustainable Renewable Energy Transition: A Mini Review". May. 2021.
[11] A. Mangra. "Design and Numerical Analysis of a Micro Gas Turbine Combustion Chamber". Dec. 2020.
[12] A. G. Vidal, J. C. Bruno, R. Best and A. Coronas. "Performance characteristics and modelling of a micro gas turbine for their integration with thermally activated cooling technologies". Jan. 2007.
[13] K.A. Al-attab, Z.A. Zainal, externally fired gas turbine technology: A review, Applied Energy, Volume 138, 2015, Pages 474-487, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2014.10.049.
[14] Jain S, Roy S, Aggarwal A, Gupta D, Kumar V, Kumar N. Study on the Parameters Influencing Efficiency of Micro-Gas Turbines: A Review 2015;V001T09A006: ASME.. https://doi.org/10.1115/POWER2015-49417.
[15] De Paepe, W., Montero Carrero, M., Bram, S., Parente, A., and Contino, F. (July 10, 2018). "Toward Higher Micro Gas Turbine Efficiency and Flexibility—Humidified Micro Gas Turbines: A Review." ASME. J. Eng. Gas Turbines Power. August 2018; 140(8): 081702. https://doi.org/10.1115/1.4038365.
[16] Gang Xiao, Tianfeng Yang, Huanlei Liu, Dong Ni, Mario Luigi Ferrari, Mingchun Li, Zhongyang Luo, Kefa Cen, Mingjiang Ni, Recuperators for micro gas turbines: A review, Applied Energy, Volume 197, 2017, Pages 83-99, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2017.03.095.
[17] Muhammad Akasha Hashim et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. **226** 012006. https://doi.org/10.1088/1757-899X/226/1/012006 .
[18] Okoroigwe EC, Madhlopa A. Advances in Biofueling of Micro Gas Turbines for Power Generation. Energy Technol 2019;7:1800689. https://doi.org/10.1002/ente.201800689.
[19] Kagan Ayaz S, Altuntas O, Caliskan H, Enhanced life cycle modelling of a micro gas turbine fuelled with various fuels for sustainable electricity production, Renewable and Sustainable Energy Reviews, Volume 149,. 111323. ISSN 2021; 1364–0321. https://doi.org/10.1016/j.rser.2021.111323.
[20] Aslanidou I, Rahman M, Zaccaria V, Kyprianidis KG. Micro Gas Turbines in the Future Smart Energy System: Fleet Monitoring, Diagnostics, and System Level Requirements. Front Mech Eng 2021;7:676853. https://doi.org/10.3389/fmech.2021.676853.
[21] Banihabib R, Assadi M. The Role of Micro Gas Turbines in Energy Transition. Energies 2022;15, no. 21:8084. https://doi.org/10.3390/en15218084.
[22] Reale F, Sannino R. "Numerical Modeling of Energy Systems Based on Micro Gas Turbine. A Review" Energies 2022;15, no. 3:900. https://doi.org/10.3390/en15030900.
[23] Robbio De, Roberta.. Micro Gas Turbine Role in Distributed Generation with Renewable Energy Sources. Energies 2023;16, no. 2:704. https://doi.org/10.3390/en16020704.
[24] S. Taamallah, K. Vogiatzaki, F.M. Alzahrani, E.M.A. Mokheimer, M.A. Habib, A.F. Ghoniem, Fuel flexibility, stability and emissions in premixed hydrogen-rich gas turbine combustion: Technology, fundamentals, and numerical simulations, Applied Energy, Volume 154, 2015, Pages 1020-1047, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2015.04.044.
[25] Sheykhpoor H, Darabkhani HG, Awan AW. Improving efficiency of micro gas turbine systems by integration of combustor and recuperator using additive manufacturing techniques. Int J Adv Manuf Technol 2023;127:23–44. https://doi.org/10.1007/s00170-023-11396-z.
[26] Hashmi MB, Mansouri M, Assadi M, Dynamic performance and control strategies of micro gas turbines: State-of-the-art review, methods, and technologies, Energy Conversion and Management: X, Volume 18,. 100376. ISSN 2023;2590–1745. https://doi.org/10.1016/j.ecmx.2023.100376.
[27] Economic and Social Council. session 25 July 2022–26 July 2023 Agenda Items 5 (a) and 6. Progress towards the Sustainable Development Goals: Towards a Rescue Plan for People and Planet; 2023. https://sdgs.un.org/goals.
[28] Goldstein, L, Hedman, B, Knowles, D, Freedman, S I, Woods, R, and Schweizer, T. Gas-Fired Distributed Energy Resource Technology Characterizations. United States: N. p., 2003. Web. doi:10.2172/15005819 .
[29] Chan T-F, Lai LL, "Permanent-Magnet Machines for Distributed Power Generation: A Review,",. IEEE Power Engineering Society General Meeting. Tampa, FL, USA 2007;2007:1–6. https://doi.org/10.1109/PES.2007.385575.
[30] McDonald C. Low-cost compact primary surface recuperator concept for microturbines. Appl Therm Eng 2000;20. https://doi.org/10.1016/S1359-4311(99)00033-2.
[31] Liss WE. Natural Gas Power Systems for the Distributed Generation Market. Corpus ID: 174770981; 1999.
[32] do Nascimento MAR, de L, dos Santos EC, Batista Gomes EE, Goulart FL, Gutirrez Velsques EI, et al. Micro Gas Turbine Engine: A Review [Internet]. Progress in Gas Turbine Performance. InTech; 2013. Available from: https://doi.org/10.5772/54444.
[33] R. D. S. Caldeira, S. L. Q. D. Souza, E. M. Martins and S. C. Marques. "Opportunities for GHG Emission Reductions in the Brazilian Graphic Industry Through a Mitigation Plan". Jan. 2022.
[34] (accessed 22 Jun 2023.
[35] "iea,. – International Energy Agency - IEA", iea.org. (accessed 22 Jun 2023.
[36] W. J. Praiselin and J. B. Edward. "A Review on Impacts of Power Quality, Control and Optimization Strategies of Integration of Renewable Energy Based Microgrid Operation". Mar. 2018.
[37] D. Maradin. "ADVANTAGES AND DISADVANTAGES OF RENEWABLE ENERGY SOURCES UTILIZATION". International Journal of Energy Economics and Policy. vol. 11. no. 3. pp. 176-183. Apr. 2021. 10.32479/ijeep.11027.

[38] A. Ghorbani, M. R. Rahimpour, Y. Ghasemi and S. Raeissi. "The Biodiesel of Microalgae as a Solution for Diesel Demand in Iran". Apr. 2018.
[39] M. Noussan, P. P. Raimondi, R. Scita and M. Hafner. "The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective". Dec. 2020.
[40] (accessed 22 Jun 2023.
[41] Leal-Arcas, Rafael and Alemany Rios, Juan and Akondo, Nelson, Energy Decentralization in the European Union (February 13, 2019). Georgetown Environmental Law Review, Vol. 32.1, 2019, Forthcoming, Queen Mary School of Law Legal Studies Research Paper No. 307/2019, Available at SSRN: https://ssrn.com/abstract=3333694.
[42] Colin F. McDonald, Low-cost compact primary surface recuperator concept for microturbines, Applied Thermal Engineering, Volume 20, Issue 5, 2000, Pages 471-497, ISSN 1359-4311, https://doi.org/10.1016/S1359-4311(99)00033-2.
[43] P.A. Pilavachi, Mini- and micro-gas turbines for combined heat and power, Applied Thermal Engineering, Volume 22, Issue 18, 2002, Pages 2003-2014, ISSN 1359-4311, https://doi.org/10.1016/S1359-4311(02)00132-1.
[44] R. Noroozian, P. Asgharian, Chapter 4 - Microturbine Generation Power Systems, Editor(s): G.B. Gharehpetian, S. Mohammad Mousavi Agah, Distributed Generation Systems, Butterworth-Heinemann, 2017, Pages 149-219, ISBN 9780128042083, https://doi.org/10.1016/B978-0-12-804208-3.00004-2.
[45] Andreoli V, Paniagua G, Bloxham M, Towards desensitization of gas turbine performance to tip Clearance: Design optimization and engine analysis, Energy Conversion and Management, Volume 245,. 114575. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114575.
[46] Romier A. R&D of high efficiency components for an intercooled recuperated CHP gas turbine for combined heat and efficient power. EC ENERGY Contract ENK5-CT2000-00070 2000.
[47] Next Generation of Micro Gas Turbines for High Efficiency, Low Emissions: Report on path to MGT commercialization. Deliverable No. 20, Relative number 4.2. Project: Marie Skłodowska-Curie Actions (MSCA) Innovative Training Networks (ITN) H2020-MSCA-ITN-2019. 861079 – NextMGT. DOI: https://doi.org/10.3030/861079.
[48] Lukas Aichmayer, James Spelling, Björn Laumert, Preliminary design and analysis of a novel solar receiver for a micro gas-turbine based solar dish system, Solar Energy, Volume 114, 2015, Pages 378-396, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2015.01.013.
[49] Alberto Boretti, Stefania Castelletto, Cost and performance of CSP and PV plants of capacity above 100 MW operating in the United States of America, Renewable Energy Focus, Volume 39, 2021, Pages 90-98, ISSN 1755-0084, https://doi.org/10.1016/j.ref.2021.07.006.
[50] Xing Ju, Chao Xu, Yangqing Hu, Xue Han, Gaosheng Wei, Xiaoze Du, A review on the development of photovoltaic/concentrated solar power (PV-CSP) hybrid systems, Solar Energy Materials and Solar Cells, Volume 161, 2017, Pages 305-327, ISSN 0927-0248, https://doi.org/10.1016/j.solmat.2016.12.004.
[51] Reddy KS, et al. Nanofluid and nanocomposite applications in solar energy conversion systems for performance enhancement: a review. International Journal of Low-Carbon Technologies 2017;12(1):1–23. https://doi.org/10.1093/ijlct/ctw007.
[52] Md Tasbirul Islam, Nazmul Huda, A.B. Abdullah, R. Saidur, A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends, Renewable and Sustainable Energy Reviews, Volume 91, 2018, Pages 987-1018, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.04.097.
[53] Abagnale C, Cameretti MC, De Robbio R, Tuccillo R. Thermal Cycle and Combustion Analysis of a Solar-Assisted Micro Gas Turbine. Energies 2017;10:773. https://doi.org/10.3390/en10060773.
[54] Mazzoni S, Cerri G, Chennaoui L. A simulation tool for concentrated solar power based on micro gas turbine engines. Energ Conver Manage 2018;174:844–54. https://doi.org/10.1016/j.enconman.2018.08.059. ISSN 0196–8904,.
[55] Ahmadi MH, Nazari MA, Ghasempour R, Pourfayaz F, Rahimzadeh M, Ming T. A review on solar-assisted gas turbines. Energy Sci Eng 2018;6:658–74. https://doi.org/10.1002/ese3.238.
[56] Iaria D, Zhou X, Al Zaili J, Zhang Q, Xiao G, Sayma A. Development of a Model for Performance Analysis of a Honeycomb Thermal Energy Storage for Solar Power Microturbine Applications. Energies 2019;12:3968. https://doi.org/10.3390/en12203968.
[57] Ssebabi B, Dinter F, van der Spuy J, Schatz M. Predicting the performance of a micro gas turbine under solar-hybrid operation. Energy 2019;177:121–35. https://doi.org/10.1016/j.energy.2019.04.064. ISSN 0360–5442,.
[58] Jinli Chen, Gang Xiao, Mario Luigi Ferrari, Tianfeng Yang, Mingjiang Ni, Kefa Cen, Dynamic simulation of a solar-hybrid microturbine system with experimental validation of main parts, Renewable Energy, Volume 154, 2020, Pages 187-200, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2019.11.022.
[59] Bustamante M, Engeda A, Liao W. Small-Scale Solar–Bio-Hybrid Power Generation Using Brayton and Rankine Cycles. Energies 2021;14:472. https://doi.org/10.3390/en14020472.
[60] Lanchi M, Al-Zaili J, Russo V, Falchetta M, Montecchi M, Aichmayer L. A Quasi-Steady State Model of a Solar Parabolic Dish Micro Gas Turbine Demonstration Plant. Energies 2022;15:1059. https://doi.org/10.3390/en15031059.
[61] He V, Gaffuri M, Van J, herle, Jürg Schiffmann, Readiness evaluation of SOFC-MGT hybrid systems with carbon capture for distributed combined heat and power, Energy Conversion and Management, Volume 278,. 116728. ISSN 2023; 0196–8904. https://doi.org/10.1016/j.enconman.2023.116728.
[62] Zhang Q, Banihabib R, Fadnes FS, Sazon TAS, Ahmed N, Assadi M, et al. 117407. ISSN 2023;0196–8904. https://doi.org/10.1016/j.enconman.2023.117407.
[63] Moradi R, Marcantonio V, Cioccolanti L, Bocci E, Integrating biomass gasification with a steam-injected micro gas turbine and an Organic Rankine Cycle unit for combined heat and power production, Energy Conversion and Management, Volume 205,. 112464. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2019.112464.
[64] S. Murugan, Bohumil Horák, A review of micro combined heat and power systems for residential applications, Renewable and Sustainable Energy Reviews, Volume 64, 2016, Pages 144-162, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.04.064.
[65] Escamilla A, Sánchez D, García-Rodríguez L, Techno-economic study of Power-to-Power renewable energy storage based on the smart integration of battery, hydrogen, and micro gas turbine technologies, Energy Conversion and Management: X, Volume 18,. 100368. ISSN 2023;2590–1745. https://doi.org/10.1016/j.ecmx.2023.100368.
[66] Comodi G, Cioccolanti L, Renzi M. Modelling the Italian household sector at the municipal scale: Micro-CHP, renewables and energy efficiency. Energy 2014;68:92–103. https://doi.org/10.1016/j.energy.2014.02.055. ISSN 0360–5442,.
[67] Mirzaee M, Zare R, Sadeghzadeh M, Maddah H, Ahmadi MH, Acıkkalp E, et al. 111919. ISSN 2019;0196–8904. https://doi.org/10.1016/j.enconman.2019.111919.
[68] Huang Z, Yang C, Yang H, Ma X. Ability of adjusting heating/power for combined cooling heating and power system using alternative gas turbine operation strategies in combined cycle units. Energ Conver Manage 2018;173:271–82. https://doi.org/10.1016/j.enconman.2018.07.062. ISSN 0196–8904,.
[69] Zhang J, Cao S, Lijun Yu, Zhou Y. Comparison of combined cooling, heating and power (CCHP) systems with different cooling modes based on energetic, environmental and economic criteria. Energ Conver Manage 2018;160:60–73. https://doi.org/10.1016/j.enconman.2018.01.019. ISSN 0196–8904,.
[70] Di Wu, Han Z, Liu Z, Zhang H. Study on configuration optimization and economic feasibility analysis for combined cooling, heating and power system. Energ Conver Manage 2019;190:91–104. https://doi.org/10.1016/j.enconman.2019.04.004. ISSN 0196–8904,.
[71] Chu S, Zhang H, Chen H, Energy, exergy, energy-saving, economic and environmental analysis of a micro-gas turbine-PV, T combined cooling, heating and power (CCHP) system under different operation strategies: Transient simulation, Energy Conversion and Management, Volume 276,. 116557. ISSN 2023;0196–8904. https://doi.org/10.1016/j.enconman.2022.116557.
[72] Javidmehr M, Joda F, Mohammadi A. Thermodynamic and economic analyses and optimization of a multi-generation system composed by a compressed air storage, solar dish collector, micro gas turbine, organic Rankine cycle, and desalination system. Energ Conver Manage 2018;168:467–81. https://doi.org/10.1016/j.enconman.2018.05.019. ISSN 0196–8904,.
[73] Masood ebrahimi, Basir Naghali, Mohammad Aryanfar, Thermoeconomic and environmental evaluation of a combined heat, power, and distilled water system of a small residential building with water demand strategy, Energy Conversion and Management, Volume 258,. 115498. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.115498.
[74] Pantaleo AM, Camporeale SM, Shah N. Thermo-economic assessment of externally fired micro-gas turbine fired by natural gas and biomass: Applications in Italy. Energ Conver Manage 2013;75:202–13. https://doi.org/10.1016/j.enconman.2013.06.017. ISSN 0196–8904,.
[75] Balli O, Caliskan H, Various thermoeconomic assessments of a heat and power system with a micro gas turbine engine used for industry, Energy Conversion and Management, Volume 252,. 114984. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2021.114984.
[76] Pirkandi J, Jokar MA, Sameti M, Kasaeian A. Fazel Kasaeian, Simulation and multi-objective optimization of a combined heat and power (CHP) system integrated with low-energy buildings, Journal of Building. Engineering 2016;5:13–23. https://doi.org/10.1016/j.jobe.2015.10.004. ISSN 2352–7102,.
[77] Yu-jie Xu, Shi-jie Zhang, Jin-ling Chi, Yun-han Xiao, Steady-state off-design thermodynamic performance analysis of a SCCP system, Applied Thermal Engineering, Volume 90, 2015, Pages 221-231, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2015.06.092.
[78] Nelson J, Johnson NG, Doron P, Stechel EB. Thermodynamic modeling of solarized microturbine for combined heat and power applications. Appl Energy 2018;212:592–606. https://doi.org/10.1016/j.apenergy.2017.12.015. ISSN 0306–2619,.
[79] Hozhabr Adhami, Shahram Khalilarya, Samad Jafarmadar, Masood Ebrahimi, Thermodynamic feasibility study of a suggested portable personal micro trigeneration system based on micro-gas turbine and micro-absorption chiller, Applied Thermal Engineering, Volume 144, 2018, Pages 45-58, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2018.08.018.
[80] You H, Han J, Liu Y. Conventional and advanced exergoeconomic assessments of a CCHP and MED system based on solid oxide fuel cell and micro gas turbine. Int J Hydrogen Energy 2020;45(21):12143–60. https://doi.org/10.1016/j.ijhydene.2020.02.138. ISSN 0360–3199,.
[81] Moradi R, Cioccolanti L, Del Zotto L, Renzi M, Comparative sensitivity analysis of micro-scale gas turbine and supercritical CO2 systems with bottoming organic Rankine cycles fed by the biomass gasification for decentralized trigeneration, Energy, Volume 266,. 126491. ISSN 2023;0360–5442. https://doi.org/10.1016/j.energy.2022.126491.
[82] Hernandez-Carrillo I, Wood C, Liu H. Development of a 1000 W organic Rankine cycle micro-turbine-generator using polymeric structural materials and its performance test with compressed air. Energ Conver Manage 2019;190:105–20. https://doi.org/10.1016/j.enconman.2019.03.092. ISSN 0196–8904,.

[83] Hassan R, Das BK, Al-Abdeli YM, Investigation of a hybrid renewable-based grid-independent electricity-heat nexus: Impacts of recovery and thermally storing waste heat and electricity, Energy Conversion and Management, Volume 252,. 115073. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2021.115073.
[84] De Paepe W, Contino F, Delattin F, Bram S, De Ruyck J. New concept of spray saturation tower for micro Humid Air Turbine applications. Appl Energy 2014;130:723–37. https://doi.org/10.1016/j.apenergy.2014.03.055. ISSN 0306–2619,.
[85] Babak DB. Performance assessment of ground source heat pump system integrated with micro gas turbine: Waste heat recovery. Energ Conver Manage 2017;152:328–41. https://doi.org/10.1016/j.enconman.2017.09.058. ISSN 0196–8904,.
[86] Himadri Roy Ghatak. Simulated process integration of wastewater electrooxidation with recuperated micro gas turbine for energy recovery. Int J Hydrogen Energy 2020;45(56):31466–80. https://doi.org/10.1016/j.ijhydene.2020.08.161. ISSN 0360–3199,.
[87] Bartolini CM, Caresana F, Comodi G, Pelagalli L, Renzi M, Vagni S. Application of artificial neural networks to micro gas turbines. Energ Conver Manage 2011;52(1):781–8. https://doi.org/10.1016/j.enconman.2010.08.003. ISSN 0196–8904,.
[88] Kartal F, Özveren U, Investigation of an integrated circulating fluidized bed gasifier, steam turbine, proton exchange membrane (PEM) fuel cell system for torrefied biomass and modeling with artificial intelligence approach, Energy Conversion and Management, Volume 263,. 115718. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.115718.
[89] Nikpey H, Assadi M, Breuhaus P. Development of an optimized artificial neural network model for combined heat and power micro gas turbines. Appl Energy 2013;108:137–48. https://doi.org/10.1016/j.apenergy.2013.03.016. ISSN 0306–2619,.
[90] Nikpey H, Assadi M, Breuhaus P, Mørkved PT. Experimental evaluation and ANN modeling of a recuperative micro gas turbine burning mixtures of natural gas and biogas. Appl Energy 2014;117:30–41. https://doi.org/10.1016/j.apenergy.2013.11.074. ISSN 0306–2619,.
[91] Olsson T, Ramentol E, Rahman M, Oostveen M, Konstantinos Kyprianidis A, data-driven approach for predicting long-term degradation of a fleet of micro gas turbines, Energy and AI, Volume 4,. 100064. ISSN 2021;2666–5468. https://doi.org/10.1016/j.egyai.2021.100064.
[92] Talebi SS, Madadi A, Tousi AM, Kiaee M, Turbine MG, fault detection and isolation with a combination of Artificial Neural Network and off-design performance analysis, Engineering Applications of Artificial Intelligence, Volume 113,. 104900. ISSN 2022;0952–1976. https://doi.org/10.1016/j.engappai.2022.104900.
[93] Md Arman Arefin & Khodadad Mostakim. Micro gas turbine for range extender electric vehicle: development of numerical model for investigating some validation parameters. Int J Sustain Eng 2020;13(5):327–36. https://doi.org/10.1080/19397038.2020.1773566.
[94] Shah RMRA, Andrew McGordon Md, Rahman M, Amor-Segan M, Jennings P, Characterisation of micro turbine generator as a range extender using an automotive drive cycle for series hybrid electric vehicle application, Applied Thermal Engineering, Volume 184,. 116302. ISSN 2021;1359–4311. https://doi.org/10.1016/j.applthermaleng.2020.116302. https://www.sciencedirect.com/science/article/pii/S1359431120337819.
[95] Shah RMRA, Qubeissi MA, McGordon A, et al. Micro Gas Turbine Range Extender Performance Analysis Using Varying Intake Temperature. Automot Innov 2020;3:356–65. https://doi.org/10.1007/s42154-020-00119-9.
[96] Ji F, Zhang X, Farong Du, Ding S, Zhao Y, Zheng Xu, et al. 115236. ISSN 2020;1359–4311. https://doi.org/10.1016/j.applthermaleng.2020.115236.
[97] Javed, A., Khalid, H. A., Arif, S. U. B., Imran, M., Rezk, A., and Khan, Z. A. (June 17, 2021). "Micro Gas Turbine Small-Scale Effects in Range Extended Electric Vehicles." ASME. *J. Energy Resour. Technol*. December 2021; 143(12): 120906. https://doi.org/10.1115/1.4051384.
[98] Heesoo Kim, Charles Nutakor, Shruti Singh, Ahti Jaatinen-Värri, Janne Nerg, Juha Pyrhönen, Jussi Sopanen, Design process and simulations for the rotor system of a high-efficiency 22 kW micro-gas-turbine range extender for electric vehicles, Mechanism and Machine Theory, Volume 183, 2023, 105230, ISSN 0094-114X, https://doi.org/10.1016/j.mechmachtheory.2023.105230.
[99] Cerinski D, Vujanović M, Petranović Z, Baleta J, Samec N, Hriberšek M, et al. 112862. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2020.112862.
[100] Guteša Božo M, Mashruk S, Zitouni S, Valera-Medina A, Humidified ammonia, hydrogen RQL combustion in a trigeneration gas turbine cycle, Energy Conversion and Management, Volume 227,. 113625. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2020.113625.
[101] Wang C, Ha C, Pan X, Qin J, Huang H, Thermodynamic analysis of chemical precooled turbine combined engine cycle, Energy Conversion and Management, Volume 239,. 114184. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114184.
[102] Shih H-Y, Liu C-R. A computational study on the combustion of hydrogen/methane blended fuels for a micro gas turbines. Int J Hydrogen Energy 2014;39(27):15103–15. https://doi.org/10.1016/j.ijhydene.2014.07.046. ISSN 0360–3199,.
[103] Maria Cristina Cameretti, Raffaele Tuccillo, Combustion features of a bio-fuelled micro-gas turbine, Applied Thermal Engineering, Volume 89, 2015, Pages 280-290, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2015.05.057.
[104] Enagi II, Al-attab KA, Zainal ZA. Combustion chamber design and performance for micro gas turbine application. Fuel Process Technol 2017;166:258–68. https://doi.org/10.1016/j.fuproc.2017.05.037. ISSN 0378–3820,.
[105] Bo, A., Giacomazzi, E., Messina, G., and Di Nardo, A. (August 20, 2018). "Analysis of a Fuel Flexible Micro Gas Turbine Combustor Through Numerical Simulations." ASME. J. Eng. Gas Turbines Power. December 2018; 140(12): 121504. https://doi.org/10.1115/1.4040737.
[106] Ajvad M, Shih H-Y. Modeling syngas combustion performance of a can combustor with rotating casing for an innovative micro gas turbine. Int J Hydrogen Energy 2020;45(55):31188–201. https://doi.org/10.1016/j.ijhydene.2020.08.113. ISSN 0360–3199,.
[107] Seliger-Ost, H., Kutne, P., Zanger, J., and Aigner, M. (March 31, 2021). "Experimental Investigation of the Impact of Biogas on a 3 kW Micro Gas Turbine FLOX®-Based Combustor." ASME. J. Eng. Gas Turbines Power. August 2021; 143(8): 081020. https://doi.org/10.1115/1.4049927.
[108] Enagi II, Al-attab KA, Zainal ZA, Teoh YH, Palm biodiesel spray and combustion characteristics in a new micro gas turbine combustion chamber design, Energy, Volume 254, Part B,. 124335. ISSN 2022;0360–5442. https://doi.org/10.1016/j.energy.2022.124335.
[109] Liu Y, Nikolaidis T, Madani SH, Sarkandi M, Gamil A, Sainal MF, et al. Multi-Fidelity Combustor Design and Experimental Test for a Micro Gas Turbine System. Energies 2022;15:2342. https://doi.org/10.3390/en15072342.
[110] Alessio Pappa, Marie Cordier, Pierre Bénard, Laurent Bricteux, Ward De Paepe, How do water and CO2 impact the stability and emissions of the combustion in a micro gas turbine? — A Large Eddy Simulations comparison, Energy, Volume 248. 123446. ISSN 2022;0360–5442. https://doi.org/10.1016/j.energy.2022.123446.
[111] Yanzhao Yang Fu, Chen JY, Song Y, Guo Z, Design and experiment study of a micro radial-flow turbine for a SOFC-MGT turbine hybrid system, Energy Conversion and Management, Volume 266,. 115861. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.115861.
[112] Jubori AA, Daabo A, Al-Dadah RK, Mahmoud Sa, Ennil AB. Development of micro-scale axial and radial turbines for low-temperature heat source driven organic Rankine cycle. Energ Conver Manage 2016;130:141–55. https://doi.org/10.1016/j.enconman.2016.10.043. ISSN 0196–8904,.
[113] Park JS, Park S, Kim KM, Choi BS, Cho HH. Effect of the thermal insulation on generator and micro gas turbine system. Energy 2013;59:581–9. https://doi.org/10.1016/j.energy.2013.07.019. ISSN 0360–5442,.
[114] Lee, D., Lim, H., Choi, B., Kim, B., Park, J., and Bang, J. (January 24, 2017). "Thermal Behavior of Radial Foil Bearings Supporting an Oil-Free Gas Turbine: Design of the Cooling Flow Passage and Modeling of the Thermal System." ASME. J. Eng. Gas Turbines Power. June 2017; 139(6): 061902. https://doi.org/10.1115/1.4035324.
[115] Kim MJ, Kim JH, Kim TS. The effects of internal leakage on the performance of a micro gas turbine. Appl Energy 2018;212:175–84. https://doi.org/10.1016/j.apenergy.2017.12.029. ISSN 0306–2619,.
[116] Cheng H, Li Z, Zhou C, Xingen Lu, Zhao S, Han Ge, et al. 120353. ISSN 2023;1359–4311. https://doi.org/10.1016/j.applthermaleng.2023.120353.
[117] Liu T, Zhang G, Li Y, Yang Y. Performance analysis of partially recuperative gas turbine combined cycle under off-design conditions. Energ Conver Manage 2018;162:55–65. https://doi.org/10.1016/j.enconman.2018.01.075. ISSN 0196–8904,.
[118] Zhang G, Zheng J, Xie A, Yang Y, Liu W. Thermodynamic analysis of combined cycle under design/off-design conditions for its efficient design and operation. Energ Conver Manage 2016;126:76–88. https://doi.org/10.1016/j.enconman.2016.07.066. ISSN 0196–8904,.
[119] Bosheng Su, Han W, He H, Jin H, Chen Z, Shaohui Yang A, et al. 112394. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2019.112394.
[120] Hosseinimaab SM, Tousi AM, A new approach to off-design performance analysis of gas turbine engines and its application, Energy Conversion and Management, Volume 243,. 114411. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114411.
[121] Do KH, Choi B-I, Han Y-S, Kim T. Experimental investigation on the pressure drop and heat transfer characteristics of a recuperator with offset strip fins for a micro gas turbine. Int J Heat Mass Transf 2016;103:457–67. https://doi.org/10.1016/j.ijheatmasstransfer.2016.07.071. ISSN 0017–9310,.
[122] Taehoon Kim, Byung-Il Choi, Yong-Shik Han, Kyu Hyung Do, Experimental and analytical investigation of a wavy fin recuperator for a micro gas turbine, International Journal of Heat and Mass Transfer, Volume 148. 118998. ISSN 2020;0017–9310. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118998.
[123] Xiao G, Yang T, Liu H, Ni D, Ferrari ML, Li M, et al. Recuperators for micro gas turbines: A review. Appl Energy 2017;197:83–99. https://doi.org/10.1016/j.apenergy.2017.03.095. ISSN 0306–2619,.
[124] Lagerström, G, & Xie, M. "High Performance and Cost-Effective Recuperator for Micro-Gas Turbines." Proceedings of the ASME Turbo Expo 2002: Power for Land, Sea, and Air. Volume 1: Turbo Expo 2002. Amsterdam, The Netherlands. June 3–6, 2002. pp. 1003-1007. ASME. https://doi.org/10.1115/GT2002-30402.
[125] Ferrari ML, Sorce A, Pascenti M, Massardo AF. Recuperator dynamic performance: Experimental investigation with a microgas turbine test rig. Appl Energy 2011;88(12):5090–6. https://doi.org/10.1016/j.apenergy.2011.07.016. ISSN 0306–2619,.
[126] Ferrari, M. L., Pascenti, M., Magistri, L., and Massardo, A. F. (November 5, 2009). "Micro Gas Turbine Recuperator: Steady-State and Transient Experimental Investigation." ASME. J. Eng. Gas Turbines Power. February 2010; 132(2): 022301. https://doi.org/10.1115/1.3156822.

[127] Shah RK. Presented at Fifth international conference on enhanced, compact and ultra-compact heat exchangers: science, engineering and technology. NJ, USA: Hoboken; 2005.
[128] Wilson, MA, Recknagle, K, & Brooks, K. "Design and Development of a Low-Cost, High Temperature Silicon Carbide Micro-Channel Recuperator." Proceedings of the ASME Turbo Expo 2005: Power for Land, Sea, and Air. Volume 1: Turbo Expo 2005. Reno, Nevada, USA. June 6–9, 2005. pp. 1029-1034. ASME. https://doi.org/10.1115/GT2005-69143.
[129] Treece, B, Vessa, P, & McKeirnan, R. "Microturbine Recuperator Manufacturing and Operating Experience." Proceedings of the ASME Turbo Expo 2002: Power for Land, Sea, and Air. Volume 1: Turbo Expo 2002. Amsterdam, The Netherlands. June 3–6, 2002. pp. 1017-1023. ASME. https://doi.org/10.1115/GT2002-30404.
[130] Hsin-Yi Shih, Yen-Chin Huang, Thermal design and model analysis of the Swiss-roll recuperator for an innovative micro gas turbine, Applied Thermal Engineering, Volume 29, Issues 8–9, 2009, Pages 1493-1499, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2008.06.029.
[131] Cocco D, Tola V. Use of alternative hydrogen energy carriers in SOFC–MGT hybrid power plants. Energ Conver Manage 2009;50(4):1040–8. https://doi.org/10.1016/j.enconman.2008.12.019. ISSN 0196–8904,.
[132] Bang-Møller C, Rokni M. Thermodynamic performance study of biomass gasification, solid oxide fuel cell and micro gas turbine hybrid systems. Energ Conver Manage 2010;51(11):2330–9. https://doi.org/10.1016/j.enconman.2010.04.006. ISSN 0196–8904,.
[133] Bang-Møller C, Rokni M, Elmegaard B. Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. Energy 2011;36(8):4740–52. https://doi.org/10.1016/j.energy.2011.05.005. ISSN 0360–5442,.
[134] Bakalis DP, Stamatis AG. Full and part load exergetic analysis of a hybrid micro gas turbine fuel cell system based on existing components. Energ Conver Manage 2012;64:213–21. https://doi.org/10.1016/j.enconman.2012.04.004. ISSN 0196–8904,.
[135] Di Carlo A, Borello D, Bocci E. Process simulation of a hybrid SOFC/mGT and enriched air/steam fluidized bed gasifier power plant. Int J Hydrogen Energy 2013;38(14):5857–74. https://doi.org/10.1016/j.ijhydene.2013.03.005. ISSN 0360–3199,.
[136] Sanaye S, Katebi A. 4E analysis and multi objective optimization of a micro gas turbine and solid oxide fuel cell hybrid combined heat and power system. J Power Sources 2014;247:294–306. https://doi.org/10.1016/j.jpowsour.2013.08.065. ISSN 0378–7753,.
[137] Facchinetti E, Favrat D, Marechal F. Design and Optimization of an Innovative Solid Oxide Fuel Cell-Gas Turbine Hybrid Cycle for Small Scale Distributed Generation. Fuel Cells 2014;14:595–606. https://doi.org/10.1002/fuce.201300196.
[138] Zhou, D., Mei, J., Chen, J., Zhang, H., and Weng, S. (May 2, 2014). "Parametric Analysis on Hybrid System of Solid Oxide Fuel Cell and Micro Gas Turbine with CO2 Capture." ASME. *J. Fuel Cell Sci. Technol*. October 2014; 11(5): 051001. https://doi.org/10.1115/1.4027393.
[139] Strazza C, Del Borghi A, Costamagna P, Gallo M, Brignole E, Girdinio P. Life Cycle Assessment and Life Cycle Costing of a SOFC system for distributed power generation. Energ Conver Manage 2015;100:64–77. https://doi.org/10.1016/j.enconman.2015.04.068. ISSN 0196–8904,.
[140] Ebrahimi M, Moradpoor I. Combined solid oxide fuel cell, micro-gas turbine and organic Rankine cycle for power generation (SOFC–MGT–ORC). Energ Conver Manage 2016;116:120–33. https://doi.org/10.1016/j.enconman.2016.02.080. ISSN 0196–8904,.
[141] Barelli L, Bidini G, Ottaviano A. Integration of SOFC/GT hybrid systems in Micro-Grids. Energy 2017;118:716–28. https://doi.org/10.1016/j.energy.2016.10.100. ISSN 0360–5442,.
[142] R.A. Nastro, N. Jannelli, M. Minutillo, M. Guida, M. Trifuoggi, L. Andreassi, A.L. Facci, V.K. Krastev, G. Falcucci, Performance Evaluation of Microbial Fuel Cells Fed by Solid Organic Waste: Parametric Comparison between Three Generations, Energy Procedia, Volume 105, 2017, Pages 1102-1108, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.03.472.
[143] Otomo J, Oishi J, Miyazaki K, Okamura S, Yamada K. Coupled analysis of performance and costs of segmented-in-series tubular solid oxide fuel cell for combined cycle system. Int J Hydrogen Energy 2017;42(30):19190–203. https://doi.org/10.1016/j.ijhydene.2017.06.031. ISSN 0360–3199,.
[144] Gandiglio M, De Sario F, Lanzini A, Bobba S, Santarelli M, Blengini GA. Life Cycle Assessment of a Biogas-Fed Solid Oxide Fuel Cell (SOFC) Integrated in a Wastewater Treatment Plant. Energies 2019;12:1611. https://doi.org/10.3390/en12091611.
[145] Perna A, Minutillo M, Jannelli E, Cigolotti V, Nam SW, Yoon KJ. Performance assessment of a hybrid SOFC/MGT cogeneration power plant fed by syngas from a biomass down-draft gasifier. Appl Energy 2018;227:80–91. https://doi.org/10.1016/j.apenergy.2017.08.077. ISSN 0306–2619,.
[146] Karimi MH, Chitgar N, Emadi MA, Ahmadi P, Rosen MA. Performance assessment and optimization of a biomass-based solid oxide fuel cell and micro gas turbine system integrated with an organic Rankine cycle. Int J Hydrogen Energy 2020;45(11):6262–77. https://doi.org/10.1016/j.ijhydene.2019.12.143. ISSN 0360–3199,.
[147] You H, Han J, Liu Y, Chen D. Thermoeconomic assessment and multiobjective optimization of a CCHP and MED hybrid system based on IR-SOFC/MGT. Int J Energy Res 2022;46(3):3155–72. https://doi.org/10.1002/er.7373.
[148] K.A. Al-attab, Z.A. Zainal, Micro gas turbine running on naturally aspirated syngas: An experimental investigation, Renewable Energy, Volume 119, 2018, Pages 210-216, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2017.12.008.
[149] Okafor EC, Kunkuma KD, Somarathne A, Ratthanan R, Hayakawa A, Kudo T, et al. Control of NOx and other emissions in micro gas turbine combustors fuelled with mixtures of methane and ammonia. Combust Flame 2020;211:406–16. https://doi.org/10.1016/j.combustflame.2019.10.012. ISSN 0010–2180,.
[150] Jean-Michel Bellas, Karen N. Finney, Maria Elena Diego, Derek Ingham, Mohamed Pourkashanian, Experimental investigation of the impacts of selective exhaust gas recirculation on a micro gas turbine, International Journal of Greenhouse Gas Control, Volume 90. 102809. ISSN 2019;1750–5836. https://doi.org/10.1016/j.ijggc.2019.102809.
[151] Giorgetti S, Bricteux L, Parente A, Blondeau J, Contino F, De Paepe W. Carbon capture on micro gas turbine cycles: Assessment of the performance on dry and wet operations. Appl Energy 2017;207:243–53. https://doi.org/10.1016/j.apenergy.2017.06.090. ISSN 0306–2619,.
[152] Choi SM, Lee JS, Myong RS, et al. Schlieren visualization of micro gas turbine exhaust plume with different shapes of nozzle. J vis 2020;23:565–76. https://doi.org/10.1007/s12650-020-00648-9.
[153] Bonasio V, Ravelli S. Performance Analysis of an Ammonia-Fueled Micro GasTurbine. Energies 2022;15:3874. https://doi.org/10.3390/en15113874.
[154] Jin Lu, Zaiguo Fu, Liu J, Pan W. Influence of air distribution on combustion characteristics of a micro gas turbine fuelled by hydrogen-doped methane. Energy Rep 2022;8(Supplement 2):207–16. https://doi.org/10.1016/j.egyr.2021.11.027. ISSN 2352–4847,.
[155] Reale F, Sannino R. Water and steam injection in micro gas turbine supplied by hydrogen enriched fuels: Numerical investigation and performance analysis. Int J Hydrogen Energy 2021;46(47):24366–81. https://doi.org/10.1016/j.ijhydene.2021.04.169. ISSN 0360–3199,.
[156] Reale F. Effects of Steam Injection on the Permissible Hydrogen Content and Gaseous Emissions in a Micro Gas Turbine Supplied by a Mixture of CH4 and H2: A CFD Analysis. Energies 2022;15:2914. https://doi.org/10.3390/en15082914.
[157] Shen W, Xing C, Liu H, Liu Li, Qiming Hu, Guohua Wu, et al. 123680. ISSN 2022; 0360–5442. https://doi.org/10.1016/j.energy.2022.123680.
[158] Banihabib R, Assadi M. A Hydrogen-Fueled Micro Gas Turbine Unit for Carbon-Free Heat and Power Generation. Sustainability 2022;14:13305. https://doi.org/10.3390/su142013305.
[159] Barakat E, Jin T, Tong X, Ma C, Wang G, Experimental investigation of saturated fogging and overspray influence on part-load micro gas turbine performance, Applied Thermal Engineering, Volume 219, Part B,. 119505. ISSN 2023; 1359–4311. https://doi.org/10.1016/j.applthermaleng.2022.119505.
[160] Ali U, Font-Palma C, Somehsaraei HN, Majoumerd MM, Akram M, Finney KN, et al. Benchmarking of a micro gas turbine model integrated with post-combustion CO2 capture. Energy 2017;126:475–87. https://doi.org/10.1016/j.energy.2017.03.040. ISSN 0360–5442,.
[161] Renzi M, Patuzzi F, Baratieri M. Syngas feed of micro gas turbines with steam injection: Effects on performance, combustion and pollutants formation. Appl Energy 2017;206:697–707. https://doi.org/10.1016/j.apenergy.2017.08.214. ISSN 0306–2619,.
[162] Mirandola S, Pedrazzi S, Allesina G, Muscio A, Modeling of a hybrid externally fired gas turbine applied to a landfill and green waste management facility, Energy Conversion and Management, Volume 244,. 114483. ISSN 2021; 0196–8904. https://doi.org/10.1016/j.enconman.2021.114483.
[163] Movahed P, Avami A, Techno-economic optimization of biogas-fueled micro gas turbine cogeneration systems in sewage treatment plant, Energy Conversion and Management, Volume 218,. 112965. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2020.112965.
[164] Chiong MC, Chong CT, Jo-Han Ng Su, Lam S, Tran M-V, Chong WWF, et al. Liquid biofuels production and emissions performance in gas turbines: A review. Energ Conver Manage 2018;173:640–58. https://doi.org/10.1016/j.enconman.2018.07.082. ISSN 0196–8904,.
[165] F. Chiariello, C. Allouis, F. Reale, P. Massoli, Gaseous and particulate emissions of a micro gas turbine fuelled by straight vegetable oil–kerosene blends, Experimental Thermal and Fluid Science, Volume 56, 2014, Pages 16-22, ISSN 0894-1777, https://doi.org/10.1016/j.expthermflusci.2013.11.013.
[166] Homam Nikpey Somehsaraei, Mohammad Mansouri Majoumerd, Peter Breuhaus, Mohsen Assadi, Performance analysis of a biogas-fueled micro gas turbine using a validated thermodynamic model, Applied Thermal Engineering, Volume 66, Issues 1–2, 2014, Pages 181-190, ISSN 1359-4311, https://doi.org/10.1016/j.applthermaleng.2014.02.010.
[167] Sallevelt JLHP, Gudde JEP, Pozarlik AK, Brem G. The impact of spray quality on the combustion of a viscous biofuel in a micro gas turbine. Appl Energy 2014;132:575–85. https://doi.org/10.1016/j.apenergy.2014.07.030. ISSN 0306–2619,.
[168] Kim S, Sung T, Kim KC. Thermodynamic Performance Analysis of a Biogas-Fuelled Micro-Gas Turbine with a Bottoming Organic Rankine Cycle for Sewage Sludge and Food Waste Treatment Plants. Energies 2017;10:275. https://doi.org/10.3390/en10030275.
[169] Buffi M, Cappelletti A, Rizzo AM, Martelli F, Chiaramonti D. Combustion of fast pyrolysis bio-oil and blends in a micro gas turbine. Biomass Bioenergy 2018;115:174–85. https://doi.org/10.1016/j.biombioe.2018.04.020. ISSN 0961–9534,.
[170] Zhu, S, & Acharya, S. "Effects of Hydrogen Addition on Swirl-Stabilized Flame Properties." Proceedings of the ASME Turbo Expo 2010: Power for Land, Sea, and Air. Volume 2: Combustion, Fuels and Emissions, Parts A and B. Glasgow, UK. June 14–18, 2010. pp. 1277-1287. ASME. https://doi.org/10.1115/GT2010-23686.
[171] Beita J, Talibi M, Sadasivuni S, Balachandran R. Thermoacoustic Instability Considerations for High Hydrogen Combustion in Lean Premixed Gas Turbine Combustors: A Review. Hydrogen 2021;2:33–57. https://doi.org/10.3390/hydrogen2010003.

[172] Ranga Dinesh KKJ, Jiang X, Kirkpatrick MP, Malalasekera W. Combustion characteristics of H2/N2 and H2/CO syngas nonpremixed flames. Int J Hydrogen Energy 2012;37(21):16186–200. https://doi.org/10.1016/j.ijhydene.2012.08.027. ISSN 0360–3199,.
[173] Karyeyen S, Ilbas M. Application of distributed combustion technique to hydrogen-rich coal gases: A numerical investigation. Int J Hydrogen Energy 2020; 45(5):3641–50. https://doi.org/10.1016/j.ijhydene.2019.02.073. ISSN 0360–3199,.
[174] Zamfirescu C, Dincer I. Ammonia as a green fuel and hydrogen source for vehicular applications. Fuel Process Technol 2009;90(5):729–37. https://doi.org/10.1016/j.fuproc.2009.02.004. ISSN 0378–3820,.
[175] Osamu Kurata, Norihiko Iki, Takayuki Matsunuma, Takahiro Inoue,Taku Tsujimura, Hirohide Furutani, Hideaki Kobayashi, Akihiro Hayakawa, Performances and emission characteristics of NH3–air and NH3CH4–air combustion gas-turbine power generations, Proceedings of the Combustion Institute, Volume 36, Issue 3, 2017, Pages 3351-3359, ISSN 1540-7489, https://doi.org/10.1016/j.proci.2016.07.088.
[176] Ekenechukwu C. Okafor, K.D. Kunkuma A. Somarathne, Akihiro Hayakawa, Taku Kudo, Osamu Kurata, Norihiko Iki, Hideaki Kobayashi, Towards the development of an efficient low-NOx ammonia combustor for a micro gas turbine, Proceedings of the Combustion Institute, Volume 37, Issue 4, 2019, Pages 4597-4606, ISSN 1540-7489, https://doi.org/10.1016/j.proci.2018.07.083.
[177] Ayaz, Süleyman & Altuntaş, Önder & Caliskan, Hakan. (2020). Thermoecologic Assessment and Life Cycle–Based Environmental Pollution Cost Analysis of Microgas Turbine. Journal of Environmental Engineering. 146. 10.1061/(ASCE)EE.1943-7870.0001611. https://doi.org/10.1061/(ASCE)EE.1943-7870.000161.
[178] Kurata, O, Iki, N, Fan, Y, Matsunuma, T, Inoue, T, Tsujimura, T, Furutani, H, Kawano, M, Arai, K, Okafor, EC, Hayakawa, A, & Kobayashi, H. "Start-Up Process of 50kW-Class Gas Turbine Firing Ammonia Gas." Proceedings of the ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition. Volume 6: Ceramics and Ceramic Composites; Coal, Biomass, Hydrogen, and Alternative Fuels; Microturbines, Turbochargers, and Small Turbomachines. Virtual, Online. June 7–11, 2021. V006T19A012. ASME. https://doi.org/10.1115/GT2021-59448.
[179] Seljak, T., Pavalec, K., Buffi, M., Valera-Medina, A., Chiaramonti, D., and Katrašnik, T. (October 5, 2018). "Challenges and Solutions for Utilization of Bioliquids in Microturbines." ASME. *J. Eng. Gas Turbines Power*. March 2019; 141 (3): 031401. https://doi.org/10.1115/1.4041312.
[180] Enagi II, Al-attab KA, Zainal ZA. Liquid fuels spray and combustion characteristics in a new micro gas turbine combustion chamber design. Int J Energy Res 2019;43: 3365–80. https://doi.org/10.1002/er.4475.
[181] Seljak T, Buffi M, Valera-Medina A, Chong CT, Chiaramonti D, Katrašnik T, et al. 109930. ISSN 2020;1364–0321. https://doi.org/10.1016/j.rser.2020.109930.
[182] Pérez-Trujillo JP, Elizalde-Blancas F, Pietra MD, Silva-Mosqueda DM, Guendulain JMG, McPhail SJ, et al. 116533. ISSN 2023;0196–8904. https://doi.org/10.1016/j.enconman.2022.116533.
[183] Li Y, Zhang G, Bai Z, Song X, Wang L, Yang Y. Backpressure adjustable gas turbine combined cycle: A method to improve part-load efficiency. Energ Conver Manage 2018;174:739–54. https://doi.org/10.1016/j.enconman.2018.07.077. ISSN 0196–8904,.
[184] Biao Zhang, Daniel Maloney, Nor Farida Harun, Nana Zhou, Paolo Pezzini, Anudeep Medam, Rob Hovsapian, Samuel Bayham, David Tucker, Rapid load transition for integrated solid oxide fuel cell – Gas turbine (SOFC-GT) energy systems: A demonstration of the potential for grid response, Energy Conversion and Management, Volume 258. 115544. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.115544.
[185] Bekiloğlu HE, Bedir H, Anlaş G. Multi-objective optimization of ORC parameters and selection of working fluid using preliminary radial inflow turbine design. Energ Conver Manage 2019;183:833–47. https://doi.org/10.1016/j.enconman.2018.12.039. ISSN 0196–8904,.
[186] Xiao G, Chen J, Ni M, Kefa Cen A, solar micro gas turbine system combined with steam injection and ORC bottoming cycle, Energy Conversion and Management, Volume 243,. 114032. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114032.
[187] Ziółkowski P, Kowalczyk T, Lemański M, Badur J. On energy, exergy, and environmental aspects of a combined gas-steam cycle for heat and power generation undergoing a process of retrofitting by steam injection. Energ Conver Manage 2019;192:374–84. https://doi.org/10.1016/j.enconman.2019.04.033. ISSN 0196–8904,.
[188] Shantanu M, Mahendra Reddy V, Karmakar S. Experimental and numerical studies on heat recirculated high intensity meso-scale combustor for mini gas turbine applications. Energ Conver Manage 2018;176:324–33. https://doi.org/10.1016/j.enconman.2018.09.032. ISSN 0196–8904,.
[189] Cao Y, Zhan J, Cao Qi, Si F, Techno-economic analysis of cascaded supercritical carbon dioxide combined cycles for exhaust heat recovery of typical gas turbines, Energy Conversion and Management, Volume 258,. 115536. ISSN 2022; 0196–8904. https://doi.org/10.1016/j.enconman.2022.115536.
[190] Li Y, Wang L, Sharma S, Zhang G, Zhang L, Maréchal F, et al. 116036. ISSN 2022; 0196–8904. https://doi.org/10.1016/j.enconman.2022.116036.
[191] Kovács VB, Hidegh GT, Rácz E, Szücs B, Csókai V, Józsa V, et al. 117568. ISSN 2023;0196–8904. https://doi.org/10.1016/j.enconman.2023.117568.
[192] Cioccolanti L, Tascioni R, Moradi R, Jurasz J, Investigating the hybridisation of micro-scale concentrated solar trigeneration systems and wind turbines for residential applications using a dynamic model, Energy Conversion and Management, Volume 269,. 116159. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.116159.
[193] Javadi MA, Khodabakhshi S, Ghasemiasl R, Jabery R, Sensivity analysis of a multi-generation system based on a gas, hydrogen-fueled gas turbine for producing hydrogen, electricity and freshwater, Energy Conversion and Management, Volume 252,. 115085. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2021.115085.
[194] Kheiri R, Saray RK, Kashani BO, Thermo-economic-environmental analysis of a new tri-generation seasonal system with gas turbine prime mover based on municipal solid waste gasification, Energy Conversion and Management, Volume 265,. 115755. ISSN 2022;0196–8904. https://doi.org/10.1016/j.enconman.2022.115755.
[195] Huang ZF, Wan YD, Soh KY, Chua KJ, Hybrid operating method to improve the part-load performance of gas turbine based combined cooling and power system, Energy Conversion and Management, Volume 226,. 113506. ISSN 2020; 0196–8904. https://doi.org/10.1016/j.enconman.2020.113506.
[196] Li Y, Zhang G, Wang L, Yang Y, Part-load performance analysis of a combined cycle with intermediate recuperated gas turbine, Energy Conversion and Management, Volume 205,. 112346. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2019.112346.
[197] Uusitalo A, Zocca M, Design and numerical analysis of supersonic radial-inflow turbines for transcritical ORC processes, Energy Conversion and Management, Volume 277,. 116609. ISSN 2023;0196–8904. https://doi.org/10.1016/j.enconman.2022.116609.
[198] Sun L, Wang D, Xie Y, Thermodynamic and exergoeconomic analysis of combined supercritical CO2 cycle and organic Rankine cycle using CO2-based binary mixtures for gas turbine waste heat recovery, Energy Conversion and Management, Volume 243,. 114400. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114400.
[199] Caposciutti G, Baccioli A, Ferrari L, Desideri U, Impact of ambient temperature on the effectiveness of inlet air cooling in a co-digestion biogas plant equipped with a mGT, Energy Conversion and Management, Volume 216,. 112874. ISSN 2020; 0196–8904. https://doi.org/10.1016/j.enconman.2020.112874.
[200] Gabriele Comodi, Massimiliano Renzi, Flavio Caresana, Leonardo Pelagalli, Limiting the Effect of Ambient Temperature on Micro Gas Turbines (MGTs) Performance Through Inlet Air Cooling (IAC) Techniques: An Experimental Comparison between Fogging and Direct Expansion, Energy Procedia, Volume 75, 2015, Pages 1172-1177, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2015.07.561.
[201] Yang Du, Jiang N, Yicen Zhang Xu, Wang PZ, Wang J, Dai Y, et al. 114473. ISSN 2021;0196–8904. https://doi.org/10.1016/j.enconman.2021.114473.
[202] He T, Lin W, Energy saving research of natural gas liquefaction plant based on waste heat utilization of gas turbine exhaust, Energy Conversion and Management, Volume 225,. 113468. ISSN 2020;0196–8904. https://doi.org/10.1016/j.enconman.2020.113468.
[203] Ashkan Entezari, Ali Manizadeh, Rouhollah Ahmadi, Energetical, exergetical and economical optimization analysis of combined power generation system of gas turbine and Stirling engine, Energy Conversion and Management, Volume 159, 2018, Pages 189-203, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.01.012.
[204] Simone Pedrazzi, Giulio Allesina, Paolo Tartarini, Effects of upgrading systems on energy conversion efficiency of a gasifier - fuel cell - gas turbine power plant, Energy Conversion and Management, Volume 126, 2016, Pages 686-696, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2016.08.048.
[205] Özkan Köse, Yıldız Koç, Hüseyin Yağlı, Energy, exergy, economy and environmental (4E) analysis and optimization of single, dual and triple configurations of the power systems: Rankine Cycle/Kalina Cycle, driven by a gas turbine, Energy Conversion and Management, Volume 227, 2021, 113604, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2020.113604.
[206] A. Durante, G. Pena-Vergara, P.L. Curto-Risso, A. Medina, A. Calvo Hernández, Thermodynamic simulation of a multi-step externally fired gas turbine powered by biomass, Energy Conversion and Management, Volume 140, 2017, Pages 182-191, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.02.050.
[207] Zuming Liu, Iftekhar A. Karimi, New operating strategy for a combined cycle gas turbine power plant, Energy Conversion and Management, Volume 171, 2018, Pages 1675-1684, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.06.110.
[208] Pablo Campo, Teresa Benitez, Uisung Lee, J.N. Chung, Modeling of a biomass high temperature steam gasifier integrated with assisted solar energy and a micro gas turbine, Energy Conversion and Management, Volume 93, 2015, Pages 72-83, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2014.12.069.
[209] Riccardo Amirante, Pietro De Palma, Elia Distaso, Paolo Tamburrano, Thermodynamic analysis of small-scale externally fired gas turbines and combined cycles using turbo-compound components for energy generation from solid biomass, Energy Conversion and Management, Volume 166, 2018, Pages 648-662, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.04.055.
[210] Zefeng Wang, Wei Han, Na Zhang, Meng Liu, Hongguang Jin, Proposal and assessment of a new CCHP system integrating gas turbine and heat-driven cooling/power cogeneration, Energy Conversion and Management, Volume 144, 2017, Pages 1-9, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.04.043.
[211] Tailu Li, Jian Liu, Jianqiang Wang, Nan Meng, Jialing Zhu, Combination of two-stage series evaporation with non-isothermal phase change of organic Rankine cycle to enhance flue gas heat recovery from gas turbine, Energy Conversion and Management, Volume 185, 2019, Pages 330-338, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2019.02.006.
[212] Evangelos Bellos, Christos Tzivanidis, Kimon A. Antonopoulos, Parametric analysis and optimization of a solar assisted gas turbine, Energy Conversion and

Management, Volume 139, 2017, Pages 151-165, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.02.042.
[213] D. Roy S. Samanta S. Ghosh Performance assessment of a biomass-fuelled distributed hybrid energy system integrating molten carbonate fuel cell, externally fired gas turbine and supercritical carbon dioxide cycle, Energy Conversion and Management, Volume 211, 112740 ISSN 0196–8904 2020 10.1016/j.enconman.2020.112740.
[214] Omar Behar, A novel hybrid solar preheating gas turbine, Energy Conversion and Management, Volume 158, 2018, Pages 120-132, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.11.043.
[215] Agustín M. Delgado-Torres, The effects of the ideal gas model with constant heat capacities on fuel efficiency optimization of the open-cycle gas turbine, Energy Conversion and Management, Volume 195, 2019, Pages 198-209, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2019.04.088.
[216] Jamasb Pirkandi, Mostafa Mahmoodi, Mohammad Ommian, Thermo-economic performance analysis of a gas turbine generator equipped with a pressurized and an atmospheric solid oxide fuel cell, Energy Conversion and Management, Volume 136, 2017, Pages 249-261, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.01.013.
[217] T.Z. Kaczmarczyk G. Żywica E. Ihnatowicz Experimental study of a low-temperature micro-scale organic Rankine cycle system with the multi-stage radial-flow turbine for domestic applications, Energy Conversion and Management, Volume 199, 111941 ISSN 0196–8904 2019 10.1016/j.enconman.2019.111941.
[218] Ragini Singh, Onkar Singh, Comparative study of combined solid oxide fuel cell-gas turbine-Organic Rankine cycle for different working fluid in bottoming cycle, Energy Conversion and Management, Volume 171, 2018, Pages 659-670, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.06.009.
[219] Mohammad Abbasi, Mahmood Chahartaghi, Seyed Majid Hashemian, Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers, Energy Conversion and Management, Volume 173, 2018, Pages 359-374, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.07.095.
[220] Xusheng Wang, Cheng Yang, Manman Huang, Xiaoqian Ma, Off-design performances of gas turbine-based CCHP combined with solar and compressed air energy storage with organic Rankine cycle, Energy Conversion and Management, Volume 156, 2018, Pages 626-638, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2017.11.082.
[221] S. Barakat, Ahmed Ramzy, A.M. Hamed, S.H. El Emam, Enhancement of gas turbine power output using earth to air heat exchanger (EAHE) cooling system, Energy Conversion and Management, Volume 111, 2016, Pages 137-146, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2015.12.060.
[222] Yunru Chen, Meng Wang, Vincenzo Liso, Sheila Samsatli, Nouri J Samsatli, Rui Jing, Jincan Chen, Ning Li, Yingru Zhao, aParametric analysis and optimization for exergoeconomic performance of a combined system based on solid oxide fuel cell-gas turbine and supercritical carbon dioxide Brayton cycle, Energy Conversion and Management, Volume 186, 2019, Pages 66-81, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2019.02.036.