Techno-Economic Assessment and Fuel Flexibility Analysis of Micro-Combined Heat and Power (Micro-CHP) Systems for Sustainable Domestic Energy Applications

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A thesis submitted in partial fulfilment of the requirements of Staffordshire University for the degree of Doctor of Philosophy

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ABSTRACT

This doctoral research provides a detailed examination of the background, motivation, aims, objectives, scope, and limitations of the study, along with the research framework, flowchart, and thesis structure. It introduces micro-Combined Heat and Power (micro-CHP) systems, emphasising their role in improving energy efficiency and reducing carbon emissions. An in-depth review is conducted on four primary prime movers commonly employed in residential micro-CHP systems: internal combustion engines (ICE), Stirling engines (SE), fuel cells (FC), and micro-gas turbines (MGT). These technologies are critically assessed in terms of their characteristics, operational performance, and suitability for household integration.

The study further explores the properties, efficiency, and operational flexibility of micro-CHP systems, with particular emphasis on MGT and FC technologies. It investigates the integration of these systems with biofuel-based renewable energy sources to enhance sustainability. Process simulations and energy-exergy analyses were carried out using Aspen Plus (Advanced System for Process Engineering), while GasTurb software was utilised for performance evaluation.

Two case studies were analysed: one combining an MGT-based CHP system with a Proton Exchange Membrane (PEM) electrolyser and fuel cell, and another featuring a standalone residential MGT. Hydrogen showed strong environmental and efficiency benefits, while hythane offered a balanced transitional fuel. Natural gas (NG) and methane delivered higher efficiencies but faced emission challenges. Recuperator integration improved performance via lean combustion. The findings confirm micro-CHP systems' fuel flexibility and potential for low-emission, high-efficiency residential energy aligned with net-zero goals.

Furthermore, the research explores strategies to improve the environmental performance of MGT and FC systems by examining biofuel production methods such as biomass conversion and anaerobic digestion (AD). Key technical challenges, risk factors, and economic implications are evaluated using Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) analysis and Multi-Criteria Decision Analysis (MCDA) to identify the most viable micro-CHP configurations for residential applications.

This doctoral project serves as a detailed resource, offering a comparative analysis of diverse micro-CHP technologies and presenting a road map for their advancement.

PUBLICATIONS:

- **Muhammad Asim Khan**, Hamidreza Gohari Darabkhani, Micro Combined Heat and Power (micro-CHP) Systems for Household Applications: Techno-economic and Risk Assessment of the Main Prime Movers, *International Journal of Green Energy*, 2023, pages 1463-1475. https://doi.org/10.1080/15435075.2023.2258177.
- **Muhammad Asim Khan**, Linus Onwuemezie, Hamidreza Gohari Darabkhani, Low-carbon fuelled MGT-CHP system coupled with PEM electrolyser and fuel cell units: A fuel flexibility and performance study, *International Journal of Hydrogen Energy*, 2024, vol. 58, pages 1277-1283. https://doi.org/10.1016/j.ijhydene.2024.01.080.

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ACRONYMS AND ABBREVIATIONS

AC	Alternating current, air conditioning
AD	Anaerobic digestion
AES	Advanced Energy System
AFC	Alkaline fuel cell
ALC	Aggregate load control
ASPEN	Advanced system for process engineering
BDC	Bottom dead centre
BEIS	Business, Energy & Industrial Strategy
BMP	Biochemical methane potential
CAGR	Compound annual growth rate
CC	Combustion chamber
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CHP	Combined heat and power
CNG	Compressed natural gas
COD	Chemical oxygen demand
COP	Climate Change Conference
DC	Direct current
DESNZ	Department for Energy Security and Net Zero
DF	Dark fermentation
DG	Distributed generation
ECO	Energy Company Obligation
EG	Electric grid
EOS	Equations of state
ETN	European Turbine Network
EU	European Union
FAME	Fatty acid methyl ester
FC	Fuel cell
FITs	Feed-in tariffs
GC-TCD	Gas chromatography with a thermal conductivity detector
GDP	Gross domestic production
GE	Gas engine
GHG	Greenhouse gas
GT	Gas turbine
HHV	Higher heating value (kJ/kg)
HP	High-pressure
HPC	High-pressure compressor

HPT	High-pressure turbine
HRSG	Heat recovery steam generator
HRT	Hydraulic retention time
H-S	Enthalpy-entropy
HVO	Hydrogenated vegetable oil
ICE	Internal combustion engine
IEA	International Energy Agency
IP	Intermediate-pressure
IEA	International energy agency
ISO	International Organisation for Standards
LCOE	Levelized cost of energy
LHV	Lower heating value (kJ/kg)
LNG	Liquefied natural gas
LP	Linear Programming
LP	Low-pressure
LPC	Low-pressure compressor
LPG	Liquefied petroleum gas
LPT	Low-pressure turbine
MCCHPS	Micro-combined cooling, heating, and power systems
MCDA	Multi-criteria decision analysis
MCFC	Molten carbonate fuel cell
MGT	Micro-gas turbine
Micro-CHP	Micro-combined heat and power
MRO	Maintenance, repair, and overhaul
MTT	Micro turbine technology
MVW	Mixed vegetable waste
NRTL	Non-random two-liquid
O&M	Operation and maintenance costs
ORC	Organic Rankine cycles
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
PEMWE	Proton exchange membrane water electrolysis
PESTLE	Political, economic, social, technological, legal, and environmental
PFD	Process flow diagram
PGU	Power generation unit
PSFC	Power-specific fuel consumption (kg/kWh)
P-V	Pressure-volume
RD&D	Research, development, and demonstration

RH	Rice husk
RHI	Renewable Heat Incentive
RPM	Revolutions per minute
SE	Stirling engine
SHD	Supplementary heating device
SOFC	Solid oxide fuel cell
STEPS	Stated Policies Scenario
SW	Sugarcane bagasse
TDC	Top dead centre
TIT	Turbine inlet temperature
T-S	Temperature-entropy
TSAF	Two-stage anaerobic fermentation
VFA	Volatile fatty acids
VOCs	Volatile organic compounds

SUBSCRIPTS

a	Ambient
atm	Atmospheric
c	Cold, Kinetic
c	Cost
e	Electrical
f	Fuel
G	Gas
h	Hot, Heat
i	Inlet, input
l, liq	Liquid
o	Outlet, output
p	Primary
ph	Preheater
th	Thermal

GENERAL SYMBOLS

A	Area (m^2)
b(t)	Sum of the energy (J)
c_p	Specific heat capacity at constant pressure (J/(kg·K))
E	Energy (J)
F	Faraday constant (C/mol)
ΔG	Gibbs free-energy change (J/mol or kJ/mol)
H	Enthalpy (J or kJ/mol)
ΔH	Enthalpy change (kJ/mol)
h	Specific Enthalpy (kJ/kg)
m	Mass (kg)
$\dot{m}$	Mass Flow Rate (kg/s)
N	Number
P	Pressure (Pa or bar or atm)
P	Power (W)
P/H	Power-to-heat ratios
PR	Pressure Ratio
Q	Heat (J)
Q_{fuel}	Fuel Energy Intake (J)
Q_{th}	Useful thermal output (J)
R	Ideal Gas Constant (J/mol·K)
S	Entropy (J/K)
ΔS	Entropy change (J/K)
s	Specific Entropy (J/kg·K or kJ/kg·K)
t	Time (s)
T	Temperature (K or °C or °F)
V	Volume (m^3)
W	Work (J)
x	Quality, load factor (%)

CHEMICAL COMPONENTS

CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Isobutane
C_4H_{10}	n-Butane
C_5H_{12}	Isopentane
C_6H_{14}	Hexanes
C_5H_{12}	n-Pentane
C_7H_{16}	Heptane's
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
NG	Natural gas
NH_3	Anhydrous ammonia
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
N_2O	Nitrous Oxide
N_2O_5	Dinitrogen Pentoxide
NOx	Nitrogen Oxides
O_2	Oxygen
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SOx	Sulphur oxides

GREEK SYMBOLS

Δ	Difference, change
α	Flow angle (Degrees, °)
β	Pressure ratio
ε	Effectiveness
η	Efficiency
π	Ratio
λ	Power-to-Heat Ratio
μ	Dynamic Viscosity (Pa.s)
ν	Kinematics Viscosity (m^2/s)
ρ	Mass Density (kg/m^3)
γ	Specific Heat Ratio
ω	Rotational Speed (Revolutions per Minute, RPM)
Σ	Sum of a Series of Terms

1. CHAPTER 1: INTRODUCTION

This chapter offers an in-depth exploration of the foundational elements of the study, beginning with the background that provides the context and relevance of the research topic. It elaborates on the existing literature, key issues, and gaps in knowledge that have prompted the investigation. The motivation section highlights the driving factors behind the research, such as the societal, scientific, or technological needs that the study aims to address. Following this, the chapter defines the aims of the research, outlining the primary goal the study seeks to accomplish, and objectives, which detail the specific and measurable steps that will be undertaken to achieve these goals.

Furthermore, the scope of the study is outlined, clarifying the boundaries of the research, including the specific aspects or areas that will be focused on and those that will be excluded. The chapter also acknowledges the limitations of the study, detailing potential constraints such as time, resources, or methodological challenges that may influence the findings and their generalizability.

In addition to these core elements, the chapter introduces the research framework, which serves as the theoretical foundation guiding the study's approach and methodology. This framework is essential for understanding the principles and theories that underpin the research design. A flowchart is also provided to visually depict the sequence of stages in the research process, from initial concept through data collection, analysis, and conclusions.

After that, the thesis structure is outlined, providing a clear roadmap of how the entire dissertation is organised. This includes a brief description of each chapter, ensuring that readers have a detailed understanding of how the research will unfold and what to expect in each section of the thesis. This chapter, therefore, serves as a critical introduction to the entire research, setting the stage for the detailed exploration and analysis that will follow.

Finally, this chapter explores the UK's energy policies, trends in inland and final energy demand, and the growing share of low-carbon sources in the energy supply. It also assesses energy and carbon dioxide ratios to understand the relationship between energy use and emissions. Additionally, the chapter examines carbon emissions from the residential sector and highlights the potential of micro-CHP systems in enhancing energy efficiency and reducing emissions in the UK.

1.1 Background and Motivation

Global energy demand is rising swiftly due to modernisation, automation, economic growth, and social development. As reported by the International Energy Outlook, energy demand is projected to grow by 56% from 2010 to 2040, with residential, commercial, and industrial sectors contributing approximately 74% of the total utility energy usage [1,2]. Among these, the building sector is a major contributor, accounting for nearly 34% of the global energy consumption and approximately 37% of Carbon Dioxide (CO_2) emissions in 2021. With rising population levels, energy transmission losses, and inefficiencies in conventional heating systems, energy usage in buildings is expected to increase further, positioning it as the most energy-intensive sector by 2040 [2,3].

Simultaneously, climate change has become a pressing global challenge due to the continuous rise in greenhouse gas (GHG) emissions. Average global surface temperatures have been rising by around 1.2°C since pre-industrial levels, and forecasts under the Stated Policies Scenario (STEPS) indicate a potential increase of up to 2.4°C by the century's end [4]. In response, the Paris Agreement (adopted during the Climate Change Conference 21) established a global objective to restrict global warming to under 2°C, necessitating a transition to low-carbon energy technologies, improved energy efficiency, and greater integration of renewable energy sources into national and global energy systems [5]. While setting net-zero carbon dioxide (CO_2) emission targets by 2050 is essential to mitigate global warming, reaching this milestone demands a substantial decrease in CO_2 emissions, which remain the dominant contributor among all greenhouse gases across various economic sectors [6,7].

Ensuring affordable and environmentally friendly energy access has become a key objective for nations worldwide. However, the on-going decline in fossil fuel availability, coupled with their harmful ecological consequences, highlights the urgency of enhancing energy conversion efficiency and expanding the adoption of renewable resources. Electricity, a fundamental component of national energy portfolios, is still largely produced from fossil fuels, necessitating improvements in generation efficiency and waste reduction [8]. In this context, Combined Heat and Power (CHP) systems have emerged as a highly efficient solution, offering heat and electricity generation together while utilising environmentally friendly fuels such as biofuels, hydrogen (H_2), and syngas [9].

At the micro-scale (<50 kWe), micro-CHP systems are recognised as a key technology for decentralised energy generation with high efficiency and reduced emissions [9]. The UK government's micro generation strategy highlights the capabilities of micro-CHP in future smart cities, with financial incentives such as Feed-in Tariffs (FIT) promoting widespread adoption [10,11]. Among the various prime movers for micro-CHP applications, internal combustion engines (ICE), Stirling engines (SE), fuel cells (FC), and micro-gas turbines (MGT) offer distinct advantages and challenges. While ICE and SE are well-established, FC and MGT present promising opportunities due to their higher efficiency, lower emissions, and suitability for integration with renewable fuels [9].

Despite the potential benefits of micro-CHP systems, their widespread adoption faces multiple technical and economic challenges, including performance optimisation, cost-effectiveness, and seamless integration with renewable energy sources. A detailed evaluation of these prime movers, particularly MGT and FC, is required to assess their feasibility and optimise their design for residential applications [9].

This Ph.D. project aims to bridge this research gap by conducting a critical review and comparative evaluation of the four major prime movers in micro-CHP systems. Through process modelling and performance analysis utilising Advanced System for process engineering (Aspen) Plus and GasTurb software, the study will evaluate system efficiency, operational flexibility, and environmental impact. Furthermore, the integration of biofuel-based renewable energy sources will be explored to enhance the sustainability of these systems. Key technical challenges, risk assessments, and economic considerations will be examined through Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) risk analysis and Multi-Criteria Decision Analysis (MCDA) to determine the most viable micro-CHP solutions for household applications.

The outcomes of these findings aim to inform the development of next-generation micro-CHP technologies, providing valuable insights for their integration into the UK energy market. By addressing critical technical and economic barriers, this study will play a pivotal role in facilitating the transition toward a more sustainable and decentralised energy infrastructure. It not only aligns with global carbon reduction targets and energy efficiency goals but also paves the way for wider adoption of low-carbon technologies and resilience in future energy systems.

1.2 Aim of this research project

The aim of this Ph.D. project is to conduct a critical review of the four major prime movers in micro-CHP systems (internal combustion engines, Stirling engines, fuel cells, and micro-gas turbines) for residential and domestic applications. This project provides full process modelling, performance analysis, and operational flexibilities of micro-CHP systems with two major prime movers (micro-gas turbine and fuel cell). Aspen Plus software will be used for the process simulation analysis of these micro-CHP systems. Gasturb modelling will be conducted for performance analysis of the micro-gas turbine micro-CHP systems. Integration of these systems with biofuel renewable energy sources, with energy/exergy analysis of the cycles will be investigated to enhance the environmental benefits of these micro-CHP systems. The technical challenges, risk assessment, and cost analysis of these systems will also be discussed. Finally, these major prime movers are compared for household applications based on PESTLE risk analysis and a MCDA.

On completion of this project, a full analysis of micro-gas turbine and fuel cell-based micro-CHP technologies for integration into the UK energy market is presented. The outcome of this Ph.D. project will be a stand to develop the new generation of these types of micro-CHP technologies.

1.3 Objective of this research project

To achieve the aim of this Ph.D. research stated in the above section 1.1, the following steps need to be taken:

A- To conduct a critical review of the four major prime movers in micro-CHP systems, namely internal combustion engines, Stirling engines, fuel cells, and micro-gas turbines, for residential and domestic applications.

B- To evaluate the full process modelling, performance analysis, and operational flexibilities of micro-CHP systems employing two significant prime movers, namely micro-gas turbines and fuel cells.

C- To integrate the MGT and FC systems with biofuel renewable energy sources, while conducting energy and exergy analysis of the respective cycles.

D- To explore technical challenges, risk assessment, and cost analysis of four main prime movers in micro-CHP systems. Also comparison of four major prime movers of micro-CHP System for household applications based on PESTLE-risk analysis and MCDA to identify optimal micro-CHP technologies for household applications.

Table 1-1 indicates the points at which these objectives are achieved within the study, while also highlighting the novel contributions of the research, including new methodologies, improved analytical approaches, or unique insights that distinguish this work from existing studies.

Table 1-1: **Chapters refer back to objectives and novelty**

Objectives	Novelty	Objectives meet in the chapters
A	Critical discussion and comparative analysis of the four major prime movers for residential and domestic applications.	Chapter 2
B	Full process modelling, performance analysis, and operational flexibilities of MGT and FC systems are investigated.	Chapters 3, and 4
C	MGT and FC systems are integrated with different biofuels and discussed energy/exergy analysis of the cycles.	Chapter 4
D	It is the first time technical challenges, risk assessment, and cost analysis of different prime movers are explored and contrasted. Also, It is the first time the most fitting choices for household applications using PESTLE and MCDA analysis are identified.	Chapters 2, and 4

1.4 Scope and limitations of the research

The global energy demand is heavily influenced by the building sector [3]. According to the International Energy Agency (IEA) 2022 report, buildings accounted to around 34% of worldwide energy use and were responsible for approximately 37% of carbon dioxide emissions in 2021. Driven by factors such as rising population, energy transmission inefficiencies, and out-dated domestic gas boiler systems, energy demand within this sector is expected to increase, potentially making it the dominant energy consumer by 2040 [2,3]. Consequently, integrating low-carbon fuels into efficient, small-scale heat engines like micro-CHP systems, along with a broader shift towards renewable energy, is essential to curbing CO_2 and other greenhouse gas emissions [12,13].

Micro-CHP systems produce electricity while capturing the resulting waste heat for space heating and domestic hot water supply, making them well-suited for use in homes and small-scale commercial settings [9]. While micro-CHP systems offer benefits like energy efficiency and reduced carbon emissions, their commercial availability remains limited compared to traditional heating and power systems [9,14]. Their applicability is constrained by factors for example, substantial initial capital expenditure, and the necessity for continuous heating loads to maximise efficiency [15]. Major obstacles to broad implementation involve significant initial investment requirements, general lack of public awareness, installation complexities, and technical challenges, lack of standardised regulations and incentives, and competition from other energy sources. Despite these challenges, growing interest and technological advancements are expected to enhance the adoption of micro-CHPs as they become more cost-competitive [15,16].

These limitations mean that micro-CHPs may not be ideal for all situations [9,15]. As highlighted by [17], the primary drawbacks of combined heat and power systems include their capital-intensive nature and the perception that they are not "truly" sustainable, as they predominantly rely on natural gas. However, the incorporation of renewable fuels such as biogas from anaerobic digestion (AD) plants or hydrogen mixtures can address these concerns [17].

Currently, commercially available micro-CHP systems powered by renewable fuels, such as biogas or hydrogen mixtures, are limited. Manufacturers assert that the technology is feasible but requires further modifications [18,19]. In recent years, many countries have intensified research efforts focused on integrating micro gas turbine systems with other technologies to minimise the operational expenses typically associated with standalone MGT units. For example, techno-economic assessments of hybrid systems combining MGTs with renewable energy sources—such as photovoltaic panels, wind turbines, and battery storage—have shown that these configurations can achieve lower operating costs compared to systems that pair solar, wind, or batteries with diesel generators or fuel cells [20]. A portion of the reduced cost in CHP systems can also be attributed to financial incentives like feed-in tariffs, which help offset initial capital investments. In addition to cost benefits, incorporating low-carbon fuels—such as blends of natural gas with biogas, syngas, or hydrogen—into MGT-CHP setups can cut CO_2 emissions by as much as 40% [21,22].

Hydrogen (H_2) production via electrolysis is considered one of the key advancements in the reduction of carbon emissions [23]. Among the various water (H_2O) electrolysis techniques, Proton Exchange Membrane Water Electrolysis (PEMWE) stands out due to its high power density, quick response time, high purity, and ability to operate at elevated pressures. When PEMWE is integrated into a micro-CHP system, it enables the simultaneous generation of heat, electricity, and hydrogen fuel, offering greater environmental benefits than a traditional natural gas-based micro-CHP setup. In this integrated configuration, the prime mover within the micro-CHP unit generates electricity, which is exported to the grid at a comparatively lower tariff, can be used to power the electrochemical water splitting process, producing hydrogen [24]. For instance, *Nami et al.* [25] reported the combined system of PEMWE and an organic Rankine cycle with hydrogen production achieving 56.2 kg/h, with exergy and energy efficiencies of 49.2%. Similarly, Ferrero and Santarelli explored a system combining PEMWE with a high-pressure, low-temperature multi-junction solar setup, which showed enhanced system performance [26].

In a similar vein, a hybrid micro-CHP system integrated with a proton exchange membrane fuel cell (PEMFC) presents a promising solution for reducing carbon emissions and minimising noise pollution [25,27]. Such a PEM fuel cell-based micro-cogeneration setup can reduce CO_2 emissions, decrease overall energy use, and simultaneously production of heat and power using hydrogen as the fuel source [28]. For instance, *Lümmen et al.* [24] observed energy and exergy efficiencies of 76.94% and 53.86% respectively, with corresponding CO_2 emissions of just 2.8 kg/h in a micro-trigeneration (MCCHP) configuration. Moreover, when integrated with renewables like wind or solar, a hybrid system incorporating PEM electrolysis, fuel cells, and micro-CHP can achieve lower generation costs than standalone hydrogen-based micro gas turbines [24].

Developing commercially viable products in this field is time-intensive, costly, and technically challenging. It requires consultations with regulatory bodies and extensive testing to gain industry acceptance. This research focuses on improving current methodologies for measuring and addressing existing challenges. While creating a commercially available product is beyond this project's scope, the research outcomes aim to influence future product development and industry practices.

Gaining industry approval is a major challenge, yet it is integral to this research's direction [29].

Although this field presents significant challenges and complex industrial problems, this research project holds substantial academic and practical value, aiming for a realistic and achievable goal within the project's scope, supported by robust academic and industrial guidance [29].

These innovations underscore the transformative potential of hybrid systems in accelerating the transition to a sustainable, low-emission energy landscape.

1.5Research mind map

The Figure 1-1 presents a research mind map that aligns with the key objectives of this study. Within the literature review, four key thematic areas were identified for critical analysis. These include a detailed review of four major prime movers, an evaluation of the operational flexibilities of micro-gas turbines and fuel cells, the integration of MGT and FC systems with biofuel-based renewable energy sources, and an exploration of technical challenges, risk assessment, cost analysis, and a comparative study of the four prime movers using PESTLE risk analysis and MCDA. These critical areas were further broken down into components that would facilitate comprehensive research, identifying topics of interest for academic study, including journal article submissions. The literature review then aligns with the research mind map, demonstrating how the study effectively achieves its aims and objectives [30].

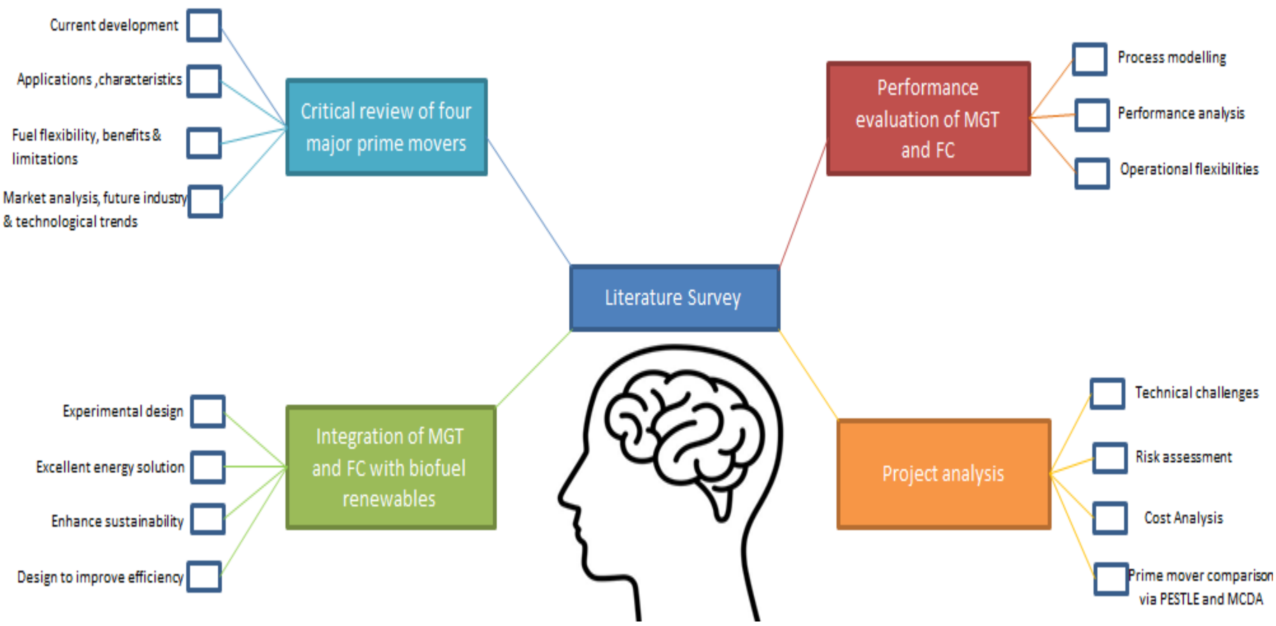

Figure 1-1: Research Mind Map, adopted from [30]

1.6 Research Flowchart

[1] Selection of the Research Topic / Problem:

a. Identifying research interests,

b. Aligning with aims and objectives,

c. Conducting a background study on the broader subject,

d. Defining the scope and limitations.

[2] Detailed Literature Review:

a. Identify relevant literature through books, peer-reviewed journals, online search engines, and conference abstracts; participate in webinars and training courses offered by the university.

b. Seek feedback from supervisors to refine research direction.

c. Develop a research strategy aligned with the action plan, incorporating techniques learned from educational workshops, including core concepts, relevant language, and analytical methods.

d. Execute the strategy systematically to gather and analyse relevant information.

e. Document key findings for the structured drafting of the literature review.

[3] Research Methodology and Approach:

a. Utilise a quantitative research framework for data-driven analysis.

b. Implement numerical modelling and simulation techniques for system evaluation.

c. Select the most suitable software tools aligned with the research strategy, incorporating supplementary software and relevant resources, including journals, meeting records, notes, and relevant applications.

[4] Results and Discussion

a. Implement a numerical or experimental methodology.

b. Validate the collected data for accuracy and reliability.

c. Verify and cross-check results for consistency.

d. Store data systematically for easy retrieval and reference.

e. Generate appropriate graphs, illustrations, and tables based on verified datasets.

f. Examine the data and offer an in-depth discussion of the observed results.

g. Ensure the utilisation of the most suitable resources for analysis.

h. Analyse quantitative research data using appropriate analytical techniques with a clear and structured format.

[5] Conclusion

a. Revise and rewrite the article as necessary, incorporating feedback and suggestions.

[6] Report Preparation and Article Writing:

a. Utilise the most relevant and credible resources,

b. Structure the report in alignment with predefined requirements,

c. Develop an article that effectively communicates findings to a diverse audience,

d. Revise and refine the article based on feedback and recommendations.

Forward View:

As depicted in the research flowchart in Figure 1-2, this research process starts with selecting an engaging topic rooted in genuine interest and aligned with established aims and objectives. Conducting thorough background reading refines the research scope and identifies potential challenges. A comprehensive literature review follows, incorporating insights from academic publications, webinars, and supervisor consultations, leading to the development of a solid research plan. The methodological approach is carefully selected, focusing on quantitative and numerical modelling techniques in conjunction with appropriate software tools and resources. The research proposal is shaped by academic training and course guidelines, and integrates research requirements with supervisor input. The next phase involves data collection through either simulation or experimental techniques, with careful validation and verification to ensure integrity. The gathered data is then analysed using advanced techniques to produce structured findings and valuable insights. The final stage involves drafting a comprehensive and accessible report or publication, refined through continuous review and feedback loops.

Reverse View for Review:

As illustrated in Figure 1-2 and discussed in this section, any incomplete execution of the steps in this process could result in significant setbacks for the research. A vague or misaligned topic can derail focus from the outset. Limited preliminary research may lead to misunderstandings of core issues. A subpar literature review may overlook essential developments or relevant methodologies. Inadequately chosen research methods can undermine the study's credibility. A rushed proposal might overlook critical ethical considerations and resource allocation. Poor data preparation threatens the reliability of the results, while weak interpretation could lead to inconclusive findings. Failing to structure the report appropriately or considering the target audience reduces the overall impact of the research. On-going feedback and revision throughout each phase are crucial to minimising these risks and achieving a successful research results.

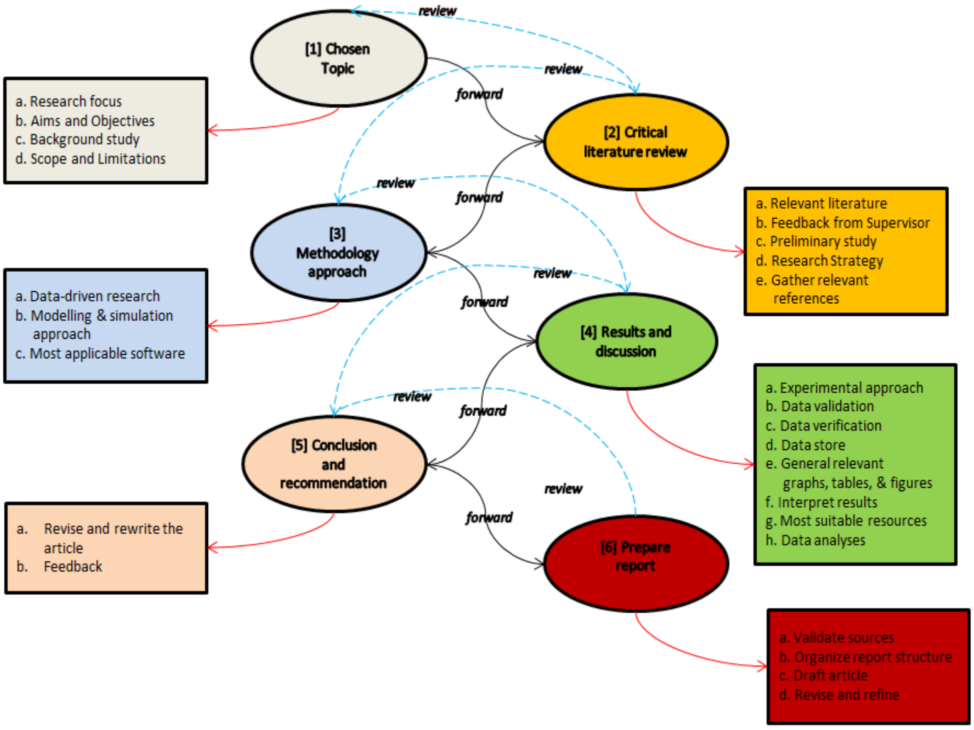

Figure 1-2: Research flow chart, adopted from [30]

1.7 Thesis Outline (Overview and structure)

This thesis is meticulously structured to provide an in-depth analysis of micro-CHP systems for domestic applications, offering a critical evaluation of major prime movers, along with detailed modelling, simulation, and techno-economic assessments. PESTLE and MCDA frameworks are employed to identify the most suitable micro-CHP technologies for households. The chapters are organised sequentially to ensure a coherent flow of knowledge and insights.

The thesis comprises five chapters, preceded by a table of contents, lists of figures, and tables, a declaration, acknowledgements, and nomenclature, and followed by the appendices after Chapter 5. The majority of the work presented here has been published in peer-reviewed journals, as outlined in the appendices.

Chapter 1: Introduction

Chapter 1 offers a comprehensive overview of the research project, outlining the background, the motivation driving the study, the primary aims and objectives, and the scope and limitations of the research. It also includes a research mind map, a flowchart of the research process, and an outline of the thesis structure. Finally, this chapter explores the UK's energy policies, consumption patterns, low-carbon energy contributions, carbon dioxide ratios, residential greenhouse gas emissions, and the role of micro-CHP systems in the country's sustainability efforts.

Chapter 2: Critical Literature Review of the Research Topic

Chapter 2 serves as the literature review, providing a comprehensive analysis of micro-CHP systems, with a specific focus on residential applications. It covers both commercially available products and emerging technologies within the micro-CHP market. The chapter explores the market segment and industry classification, the configuration of micro-CHP systems for domestic use, optimal energy distribution strategies, the differences between conventional power plants and CHP plants, the essential components of micro-CHP systems, operational methodologies, and the future potential of micro-CHP technology. Furthermore, it offers a critical evaluation of four primary prime movers—ICE, SE, FC, and MGT—examining their characteristics, applications, and future advancements. The chapter also delves into the viability of biomass, biofuels, and anaerobic digestion systems for micro-CHP applications. Lastly, it provides an in-depth analysis of the key research and demonstration challenges related to hydrogen and hythane-fuelled micro-CHP systems, identifying potential obstacles and opportunities for further development in this emerging field.

Chapter 3: Methodology

Chapter 3 offers a comprehensive overview of the methodologies used with Aspen Plus and GasTurb 14 in micro-CHP system analysis. It details the processes involved in system modelling, performance analysis, optimisation, and validation, highlighting how both software tools contribute to the understanding and improvement of micro-CHP technologies.

Chapter 4: Results and Discussion

Chapter 4 presents the development of a methodology that explores the results of process modelling, performance evaluation, and operational flexibility analysis for micro-CHP systems utilising two primary prime movers: micro-gas turbines and fuel cells. The foundation for the proposed approach is built on the requirements outlined in Chapters 2 and 3, which identify key industrial challenges that need to be addressed. The PESTLE and MCDA frameworks play a critical role in systematically evaluating various factors to identify the most appropriate solutions for residential applications. These frameworks consider political, economic, social, technological, legal, and environmental aspects (PESTLE) and compare different options through multi-criteria decision analysis (MCDA), ensuring a thorough evaluation of all relevant factors for optimal decision-making in residential use. Initial system designs are proposed, followed by modal analysis to validate the underlying design principles. Experimental validation is conducted to confirm the accuracy of the simulation results. Verification studies ensure the reliability of the simulations, leading to an extensive discussion of the outcomes and insights drawn from the analysis.

Chapter 5: Conclusion and Recommendations

The final chapter brings together the key findings from the earlier chapters. It summarises the primary conclusions of the research and presents suggestions for future work in the field of micro-CHP systems. Serving as a conclusive overview, it consolidates the contributions made throughout the study and provides insights into potential directions for continued research.

This organised structure ensures that each chapter builds upon the previous one, advancing the central theme of improving the environmental benefits of micro-CHP systems. It leads the reader through a coherent progression of concepts, from foundational theories to practical implementations, culminating in a thorough analysis of the research outcomes.

Appendices 1 and 2 provide details of the published work.

1.8 UK Energy Landscape and the Role of Micro-CHP

The UK has developed a comprehensive energy policy framework aimed at reducing carbon emissions, enhancing energy efficiency, and incorporating low-carbon technologies into the national energy infrastructure. These policies are crafted to support the country's legally binding target of achieving net-zero carbon emissions by 2050, which has resulted in notable shifts in energy consumption habits, CO_2 emissions, and the growing reliance on clean and sustainable energy alternatives.

1.8.1 UK energy policies

The UK government recently unveiled its Powering-up Britain package, which comprises several important points, which includes an Energy Security Plan as well as a Net Zero Growth Plan [31]. These primarily bring together the current policies of the government and those who are currently in the process of legislation, including the Energy Bill. But this package also introduces some new elements, one of which is the scheme of Floating Offshore Wind Manufacturing Investment. That scheme aims to support the goals of the government to achieve the target of 5 GW of floating wind range by 2030. To support investment in the necessary port infrastructure for constructing the farms of floating wind, the scheme will give 160 million GBP in grant funding [32,33].

Furthermore, the Department for Energy Security and Net Zero (DESNZ) will be implementing the suggestions put forth in the Skidmore Report to expedite the growth of solar power. This initiative is aligned with the government's aspirational goal to reach 70 GW of solar energy capacity by the year 2030. The Skidmore Report is an autonomous assessment of the UK's onward movement towards its target of net-zero carbon emissions and has provided valuable insights for this endeavour. DESNZ has confirmed its two projects for carbon capture, utilisation, and storage (CCUS). The first project is called Acorn, which is in Aberdeenshire, and the second one is Viking, which is in the Humber region. These two projects are currently being considered as a portion of Track No. 2 of its CCUS bunch sequencing task, as the other two projects have already been chosen for Track No.1 [33].

RWE is one of the leading electricity generators in the UK, which recently formed a partnership with another company called Harbour Energy in December 2022. The team of Viking CCS will find different inventive and modern methods to decarbonise the UK's gas-fired power generation [32].

1.8.2 UK inland energy consumption

In 2020, primary energy consumption experienced a significant decline of around 11% compared with 2019, because it was the cause of energy supply during COVID-19 [34,35]. Additionally, the total temperature of 2020 was higher than the total temperature of 2019, and that temperature was 0.3° [36,37]. When considering temperature adjustments, the consumption of primary energy was 10% less than in 2019, continuing the generally downward trend observed since 2005 [34]. For the last 31 years, there has been a significant rise in natural gas (NG) and primary electricity consumption, whereas the usage of oil and coal has seen a decline. However, it is worth mentioning that bioenergy and waste consumption have also experienced growth over the past decade [37]. Figure 1-3 depict the comparisons of the UK's inland energy consumption in 1990 and 2020, while Table 1-2 displays the overall inland primary energy consumption of the UK from 1990 to 2020.

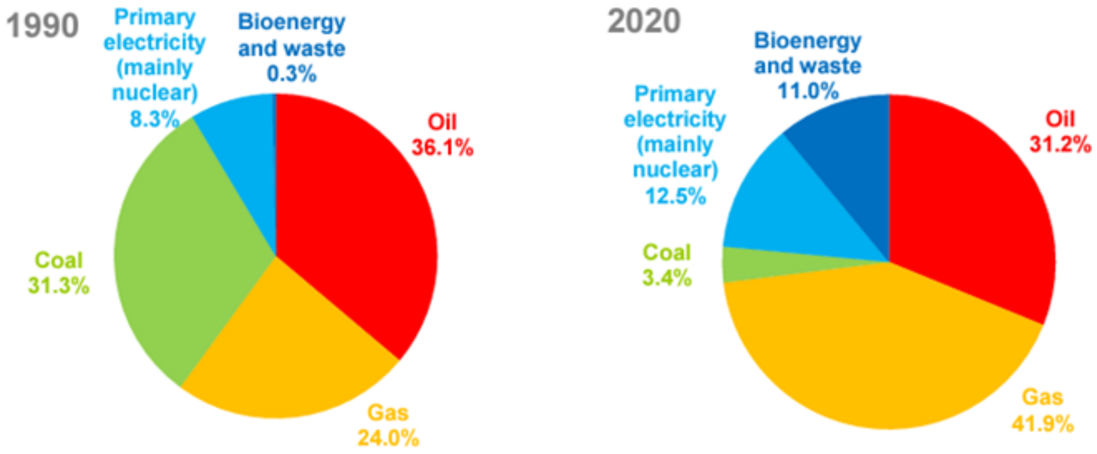

Figure 1-3: Inland energy consumption within the UK (1990 and 2020) [37]

Table 1-2: UK total inland primary energy consumption (1990 to 2020), table adopted from [37]

	Million tons of oil equivalent					
	1990	**2000**	**2010**	**2018**	**2019**	**2020**
Total inland primary energy consumption:	213.6	234.8	219.3	189.5	184.5	163.3
Conversion losses:	66.4	53.8	50.3	34.2	31.8	28.8
Distribution losses and energy industry use:		20.7	18	14.7	14.7	13.7
Total finally energy consumption:	147.3	159.4	150.3	141.1	138.8	120.9
Final consumption of which:						
Industry	38.7	35.5	27	23.1	22.4	21
Domestic sector	40.8	46.9	48.4	39.5	38.4	39.3
Transport	18.6	55.5	54.6	56.9	56.4	40.5
Services	19.2	21.5	20.2	21.6	21.4	20.2
Temperature corrected total inland consumption:	221.6	240.2	213.5	191.4	186.9	167.7

1.8.3 UK final energy consumption

In 2020, the consumption of UK final energy declined by around 13% compared with 2019, and in that ratio, the use of non-energy was not included, primarily, it was the cause of the COVID-19 impact. However, it is worth noting that there was a 2.3% increase in energy consumption within the domestic sector, attributed to the rise in home working. On the other hand, the service sector experienced a decline of 5.6%, the industry sector saw a decrease of 6.2%, and the transport sector witnessed a significant drop of 29%. The declines observed in the service and industry sectors were a result of the closure of factories, shops, markets, offices, and schools as a result of lockdown measures [37]. The substantial decrease in the transport sector mainly resulted from several travel limitations, resulting in a 60% reduction in air consumption and an 18% decrease in road consumption [38]. Overall, when adjusted for temperature, final energy consumption in 2020 decreased by 11%. Regarding the types of fuel, the final consumption of gas, which is primarily utilised for heating, decreased by 2%? Oil use also experienced a significant decline of 26%, while electricity consumption decreased by 5%. However, it is worth mentioning that the usage of bioenergy increased in all sectors except transportation [37]. Figure 1-4 shows the UK's final energy consumption from 1990 to 2020, while Table 1-3 shows the UK's final energy consumption in 2020.

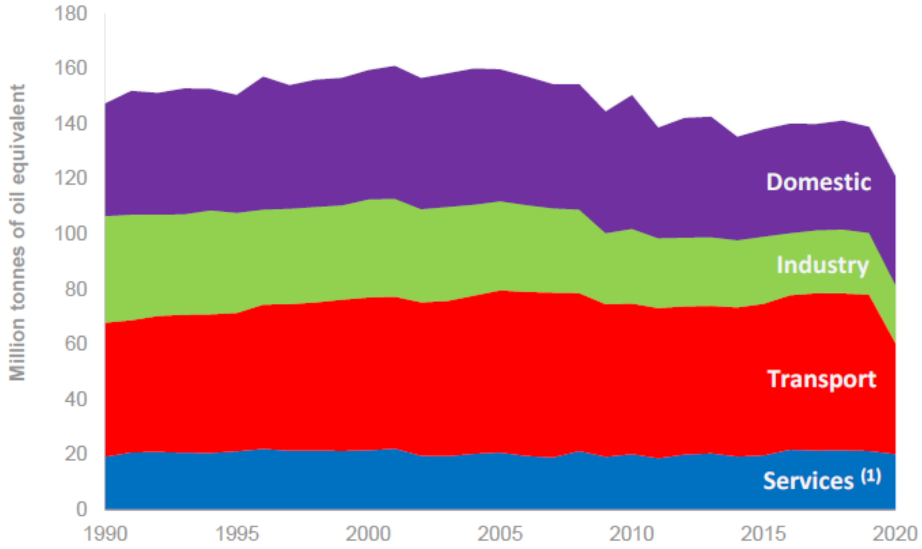

Figure 1-4: Final energy consumption within the UK (1990 and 2020) [37]

Table 1-3: UK final energy consumption of 2020, table adopted from [37]

2020	Million tons of oil equivalent				
	Industry	**Domestic**	**Transport**	**Services**	**Total**
Coal & manufactured fuels	1.2	0.5	0	0	1.6
Gas	8.1	25.7	0	7.7	14.6
Oil	2.2	2.5	37.9	3.5	46.6
Electricity	7.2	9.3	0.4	7.2	24.1
Bioenergy and heat	2.4	1.3	1.6	1.7	7
Total	**21**	**39.3**	**40.5**	**20.2**	**120.9**

1.8.4 UK energy supplied percentage from the sources of low-carbon

In 2020, the UK sourced 21.5 percent of its primary energy from sources of low carbon [39]. Out of this, bioenergy accounted for 37 percent, nuclear energy for 31 percent, and wind energy for 18 percent [40]. In 2020, there was a 3.9% increase in energy supply from biofuels, indicating a growth trend. Similarly, solar energy supply saw a 4.4% increase, which can be attributed to the expansion of capacity. However, there was a significant decline of 11% in the supply of nuclear energy. This decrease was primarily caused by multiple outages that occurred at all UK's 8 power stations throughout the year [37,41].

In 2020, there was a significant 18% increase in energy supply from wind, accompanied by a 2.5% rise in capacity. Additionally, wind speeds were recorded to be 0.8 knots higher than the previous year. It is to be noted that the UK experienced the impact of ten named storms throughout the year, making 2020 the windiest year since 2015 [37]. Figure 1-5 and Table 1-4Table 1-4 show the percentage of UK energy sourced from low-carbon outlets between 2000 and 2020.

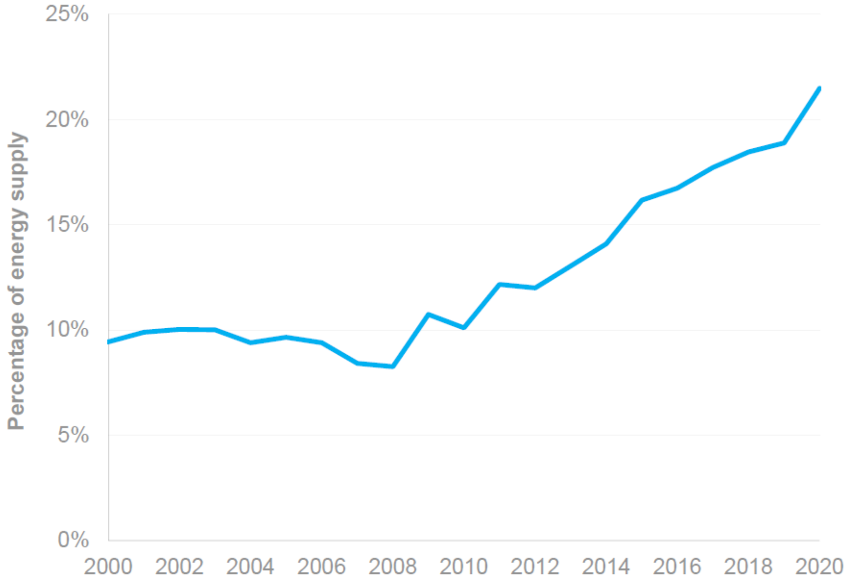

Figure 1-5: The percentage of UK energy sourced from low-carbon outlets (2000 to 2020) [37]

Table 1-4: Proportion of energy in the UK provided from low-carbon means (2000 to 2020), table adopted from [37]

						Percentage
	2000	**2005**	**2010**	**2018**	**2019**	**2020**
Nuclear	8.40%	7.80%	6.30%	7.40%	6.50%	6.60%
Wind	0.00%	0.10%	0.40%	2.60%	3.00%	4.00%
Solar	0.00%	0.00%	0.00%	0.60%	0.60%	0.70%
Hydro	0.20%	0.20%	0.10%	0.20%	0.30%	0.40%
Bioenergy	0.90%	1.60%	2.30%	6.10%	6.70%	7.80%
Transport fuels	0.00%	0.00%	0.60%	0.70%	0.90%	1.00%
Other	0.00%	0.00%	0.40%	0.80%	0.90%	1.00%
Total	**9.40%**	**9.70%**	**10.10%**	**18.50%**	**18.90%**	**21.50%**

1.8.5 UK energy and carbon dioxide ratios

The ratio of energy can be calculated by dividing temperature-adjusted consumption of primary energy by gross domestic production at fixed prices, while the carbon ratio can be determined by dividing carbon dioxide emissions by gross domestic production (GDP). Both ratios have consistently decreased over time, with the ratio of energy decreasing by approximately 2½% annually and the ratio of carbon decreasing at a little faster rate of just over 3½% annually. The decrease in these ratios can be attributed to various elements, which include advancements in the efficiency of energy and the reduced significance of energy-intensive industries. Additionally, the carbon ratio has been additionally enhanced through the greater utilisation of carbon-efficient fuels and renewable energy sources [42].

The decrease in the carbon ratio in 2020 can be ascribed generally to the significant reduction in the transportation sector during the lockdowns of COVID-19. As a result, the emissions of CO_2 from the transportation sector decreased by around 20% during COVID-19 in 2020. As per the latest data from the IEA, the energy ratio is declining in all G8 countries. It is approximated that the United Kingdom has the lowest energy ratio among the G8 nations [37]. Figure 1-6 and Table 1-5 shows the UK energy and carbon ratios from 1990-2020.

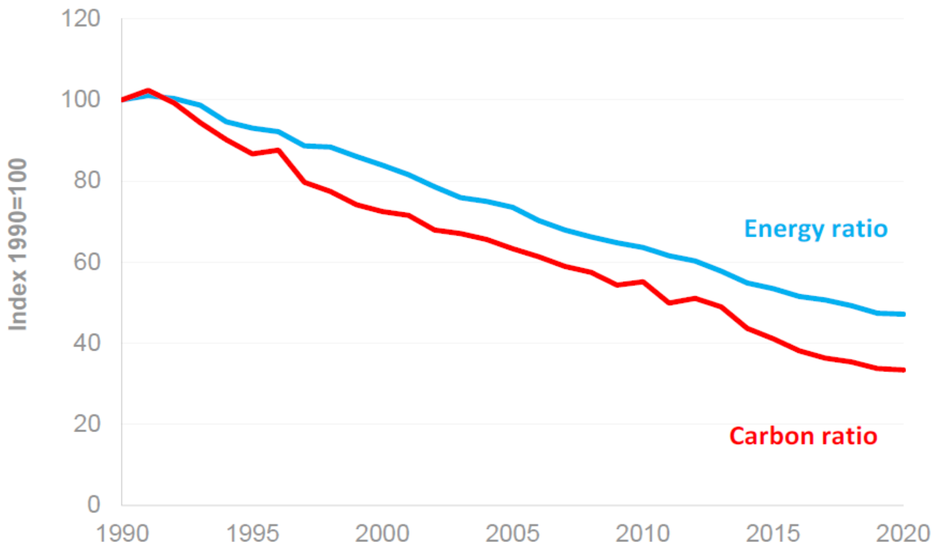

Figure 1-6: The ratios of energy and carbon within the UK (1990 to 2020) [37]

Table 1-5: The ratios of energy and carbon emissions in the UK (1990 to 2020), table adopted from [37]

					Index 1990=100	
	1990	**2000**	**2010**	**2018**	**2019**	**2020**
Primary energy consumption	100	108.4	96.3	86.4	84.4	75.7
Carbon dioxide emissions	100	93.6	83.5	62.1	60	53.6
GDP	100	129.3	151.5	175.4	178	160.4
Energy ratio	100	83.8	63.6	49.2	47.4	47.2
Carbon ratio	100	72.4	55.1	35.4	33.7	33.4

1.8.6 UK residential sector's greenhouse gas emissions

In the part of residential, the primary contributor to emissions is the utilisation of NG for heating and cooking purposes. It is important to mention that emissions from this section do not encompass the emissions generated from the production of electricity, as these emissions are accounted for in the energy supply sector [43].

In 2022, the part of residential in the UK was liable for emitting 56.4 $MtCO_2$, which accounted for 17.0% of the total CO_2 emissions. It is to be noted that there was a notable decrease of 16.5% (11.1 Mt) in territorial CO_2 emissions from the residential sector between 2022 and 2021. This reduction marks the third-largest decline since the data series began in 1990. From 1990 to 2022, there has been a significant reduction of 27.9%, which is 21.8 Mt in territorial CO_2 emissions from the residential sector. The decrease in CO_2 emissions from 2021 to 2022 can be attributed to the warmer weather experienced in 2022, resulting in reduced energy consumption for heating purposes. Additionally, higher energy prices, especially in the last quarter of 2022, may have also played a role. It is noteworthy that the average UK daily temperature was 0.9 degrees Celsius in 2022 which was more than the long-term average temperature from 1991 to 2022, and that temperature was 0.8 degrees higher than in 2021. Even if the temperatures in both years had followed long-term trends, there would still have been a 6.8% which is around 4.7 Mt decrease in emissions. It is essential to consider that residential emissions can vary from year to year because of fluctuations in weather conditions, as illustrated in the figure below. Figure 1-7 shows the actual and temperature-corrected annual CO_2 emissions from residential areas in the UK from 2009-2022 ($MtCO_2$) [44].

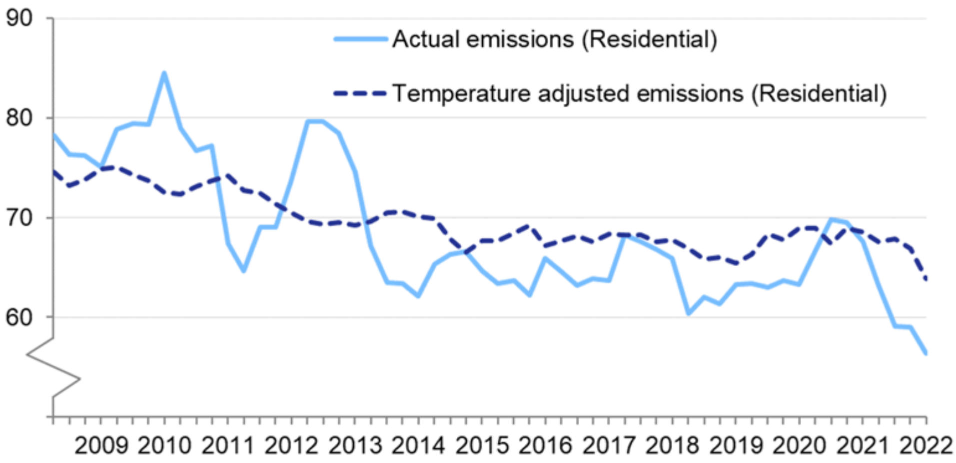

Figure 1-7: UK's real and temperature-adjusted yearly residential CO_2 territorial emissions, 2009-2022 ($MtCO_2$) [44]

1.8.7 UK and micro-CHP System

The UK has been at the forefront of adopting energy-efficient technologies and advancing sustainable energy solutions, including micro-CHP systems. In line with its goal of reaching net-zero carbon emissions by 2050, the UK government has identified micro-CHP systems as a vital component of its energy efficiency strategy, especially for residential and small commercial sectors. To encourage the adoption of these systems, the government has implemented various policies and financial incentives while addressing challenges related to the transition toward renewable energy. This section examines the role of micro-CHP in the UK, focusing on energy policies, government initiatives, and future plans.

1) UK Energy Policy and the Role of Micro-CHP

The UK's energy strategy is designed to create a sustainable, low-carbon energy system that balances economic growth with environmental goals. Micro-CHP systems are a key component in the UK's decarbonisation efforts for both heating and electricity consumption. In alignment with the Clean Growth Strategy released by the Department for Business, Energy & Industrial Strategy (BEIS), there is a strong emphasis on enhancing energy efficiency across sectors while minimising carbon emissions in homes and businesses. By producing heat and electricity together from a single energy source, micro-CHP systems significantly contribute to achieving these objectives.

The UK government continues to integrate renewable energy solutions into the national grid, and micro-CHP systems, particularly those powered by renewable fuels like biogas or hydrogen, are positioned to support this transition. As part of the broader goal of reaching carbon neutrality by 2050, micro-CHP technology is integrated into the UK's long-term for cutting greenhouse gas emissions across various industries [45].

2) Government Incentives and Support Programs

To drive the adoption of micro-CHP systems, the UK government has launched several financial incentives that aim to lower initial installation costs and improve economic feasibility. Notable programs include the Renewable Heat Incentive (RHI) and the Feed-in Tariff (FIT) scheme, both of which have significantly influenced the micro-CHP market.

a) Renewable Heat Incentive (RHI)

The RHI was launched to stimulate the adoption of renewable heating technologies, including micro-CHP. While the scheme primarily supported larger-scale renewable solutions, it was also extended to micro-CHP installations. Through RHI payments, businesses and homeowners received financial compensation for generating heat from renewable energy sources, making micro-CHP a more financially viable option [46][47].

b) Feed-in Tariffs (FITs)

The Feed-in Tariff (FIT) program, which was operational until 2019, incentivised the generation of renewable electricity, including micro-CHP. Under this scheme, households and businesses were compensated for producing electricity from renewable sources while benefiting from the combined heat and power output. Although the FIT scheme has ended, it played a key role in establishing micro-CHP as a viable and competitive energy solution in the UK [48].

c) Energy Company Obligation (ECO)

Another crucial initiative supporting micro-CHP adoption is the Energy Company Obligation (ECO), which focuses on improving energy efficiency in UK homes, particularly for lower-income households. Through the ECO program, financial assistance is provided to vulnerable households to help them install energy-efficient technologies, including micro-CHP systems. This initiative contributes to reducing fuel poverty and enhancing energy efficiency in homes that might not otherwise afford such upgrades [49].

Through these policies and programs, the UK government continues to demonstrate a strong commitment to integrating micro-CHP systems into its broader sustainability strategy, aiming for a cleaner, more efficient energy future.

2. CHAPTER 2: LITERATURE REVIEW

This chapter provides an in-depth exploration of the literature supporting the present study, focusing on four major areas of research. In alignment with the aims and objectives outlined in the introduction, this study achieves the milestones specified in section 1.3, particularly those related to part "A."

The first area of focus is micro-CHP systems for residential applications, covering a broad spectrum of topics, including an introduction to the technology, micro-CHP market segment, the configuration of micro-CHP systems for domestic use, optimisation of energy distribution strategies, distinctions between conventional power plants and CHP systems, fundamental components of micro-CHP setups, operational methodologies, and the prospective advancements in micro-CHP technology.

The second area provides a critical evaluation of four major prime movers used in micro-CHP systems: Internal Combustion Engines (ICE), Stirling Engines (SE), Fuel Cells (FC), and Micro Gas Turbines (MGT). This discussion includes an overview of each technology's including background, main components, types, applications, key characteristics, current advancements, commercially available systems, fuel flexibility, benefits and limitations, market analysis, future industry and technological trends, as well as potential advancements.

The third area offers a detailed feasibility study of biomass, biofuels, and anaerobic digestion systems, assessing their viability as sustainable energy sources for micro-CHP applications.

Finally, this chapter concludes with a comprehensive discussion on hythane- and hydrogen-fuelled micro-CHP systems, covering topics such as an introduction to hythane, its two-stage and single-stage production processes, production from organic waste, as well as key research and demonstration challenges. For hydrogen, the discussion includes an introduction to hydrogen generation methods, its use in gas turbine systems, combustion properties and challenges, utilisation pathways, and its role as an energy storage medium.

2.1 Micro-Combined Heat and Power (micro-CHP) System

This section presents a in-depth discussion on micro-CHP systems, covering topics such as an introduction to the technology, industry segmentation, global analysis of micro-CHP applications in buildings, the development of micro-CHP systems for residential use, optimisation for peak economic efficiency, their potential in the building sector, fundamental components, operational strategies, sizing considerations for both collective and residential applications, and the future prospects of micro-CHP technology.

2.1.1 Introduction

The combination of electricity and heat generation is an innovative and fast-growing approach that minimises energy losses and enhances efficiency. This method is commonly known as a CHP system. CHP technologies are largely now adopted & have significantly reduced the emissions to the environment. Moreover, CHP systems can enhance the reliability of energy supply while strengthening energy security. By simultaneously producing heat and electricity from a single fuel input, these systems deliver a more sustainable and efficient energy solution [8]. The CHP system utilises advanced technology to efficiently capture waste heat from electricity production. Then this reclaimed heat could be employed for heating spaces and hot water provision, and also can generate steam and heat for various industrial applications such as anaerobic digestion [50].

Micro-CHP is a collective title used to explain the range of innovative technologies that could produce both heat and electricity simultaneously, utilising the same source of energy. These technologies are designed to be installed in individual homes or buildings, providing an efficient and sustainable solution for energy generation. The initial result of a micro-CHP is the production of heat, along with a smaller amount of electricity; the ratio for this production is around 6:1 for household appliances [51]. Figure 2-1 depicts the micro-CHP system.

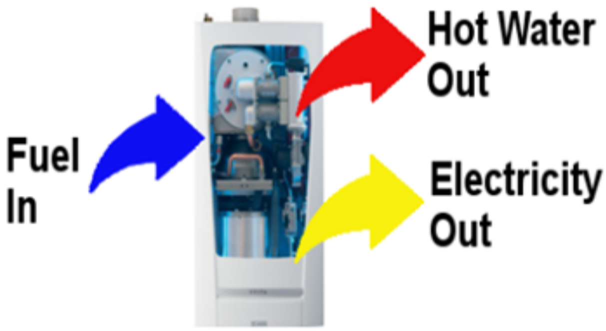

Figure 2-1: Micro-CHP system showing fuel input and heat and power output [52]

CHP systems can decrease carbon emissions by up to 30% compared to generating electricity and heat separately with a grid-connected power plant and a gas boiler. When both electricity and heat demands are met at the same location, CHP can cut down energy costs by up to 40%, with a payback period of 1–3 years [53]. Over time, advancements in CHP technology have led to well-designed systems achieving overall efficiencies between 65% and 85%, with some reaching nearly 90%. In contrast, the combined efficiency of separately produced thermal and electrical energy typically ranges from 45% to 55% [54].

The overall efficiency (η_o) of a CHP system is determined by summing the net useful electrical output, denoted as W_e (J or Watt), and the net useful thermal output, represented as $\sum Q_{th}$ (J or watt), and then dividing the total by the total fuel energy input, represented as Q_{fuel} (J or watt). This relationship is expressed by the following equation:

$$\eta_0 = (W_e + \Sigma Q_{th}) / Q_{fuel} \qquad \text{Equation 2-1}$$

The overall system efficiency of a CHP unit is defined by assessing the combined useful thermal and electrical output about the fuel consumption [55]. CHP systems exhibit high overall efficiency, and improved efficiency can significantly reduce emissions of Nitrogen Oxides (NOx), greenhouse gases, Sulphur oxides (SOx), and volatile organic compounds [56].

CHP technologies are classified based on their installed electrical capacity. Systems with an installed capacity exceeding 1 MWe are considered large-scale CHP, [56]. Accounting for 94.1% of the global CHP capacity and primarily serving industrial applications [57]. Small-scale CHP units range from 50 kWe to 1 MWe, while micro-CHP systems operate below 50 kW [56] While large-scale CHP systems have long been commercially available, micro-CHP units (<50 kW) are relatively new, providing cost-effective and low-emission electricity and thermal energy for residential and small-scale applications [58].

Once the system is warmed up, a normal domestic setup can produce around 1kW of electricity. The quantity of overall produced electricity in a year will vary depending on the duration the system can operate. Micro-CHP systems have a comparable size and shape to conventional domestic boilers, making them easy to install either on a wall or on the floor. The key distinction between a micro-CHP system and a conventional boiler lies in the fact that a micro-CHP system can simultaneously produce electricity concurrently with heating water, which is not possible with a regular boiler [51].

In the last few years, the development of the products of micro-CHP systems has been on the rise, which is defined as having a capacity of less than 50 kW for this assessment. These products utilise various prime movers, including FC, SE, ICE, MGT, and Organic Rankine Cycles (ORC). They are specifically designed to cater to the needs of residential and small commercial markets. The demand for the products of micro-CHP systems in Europe and Asia is fundamentally driven by the availability of incentives (net metering, feed-in tariffs, subsidies of capital cost, and low-interest loans) as well as relatively high energy rates. These factors have contributed to the growing popularity of micro-CHP products in these regions. With micro-CHP equipment being on the market for over ten years, global sales have reached nearly 300,000 units. Japan has accounted for 80% of these sales, followed by Europe at 15%, the US at 0.2%, and the rest of the world making up the remaining percentage. However, the micro-CHP market in the US has not gained much momentum yet. While there are over twenty micro-CHP products available or emerging worldwide, only six out of these twenty systems are present & accessible in the US. Figure 2-2 shows the worldwide activity in the field of micro-CHP products & technologies [59].

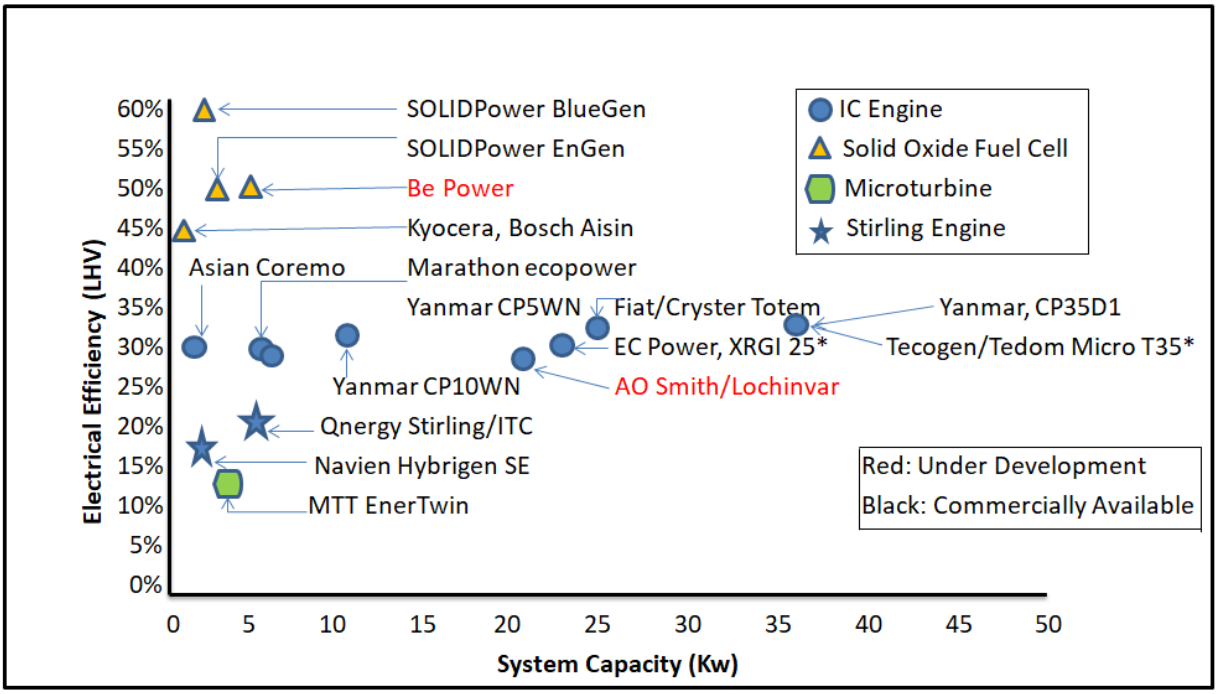

Figure 2-2: Current available and under-development products of micro-CHP, adopted from [59]

As the significance of building energy consumption continues to grow, the household sector is becoming increasingly appealing. Micro-CHP is widely regarded as the future of domestic energy supply [60]. In residential settings, micro-CHP systems typically utilise mains gas or liquefied petroleum gas (LPG) as their primary power source. However, there are now models available that can be powered by bio-liquids or oil, like as biodiesel. While LPG & gas are not sources of renewable energy, it is to noting that this technology is regarded as a low-carbon option. This is because it can achieve higher efficiency levels, surpassing those achievable by solely burning fossil fuel for heat and relying exclusively on electricity from the national grid [51].

2.1.2 Micro-CHP market segment:

The micro-CHP market size is determined by its capacity, which can be categorised into three ranges: less than 2 kW, 2-10 kW, and greater than 10-50 kW. The fuel sources for micro-CHP systems include natural gas (NG) and LPG, coal, renewable resources, and oil. The prime movers used in micro-CHP systems are the ICE, SE, FC, and other technologies like micro gas turbines (MGT). Micro-CHP systems find applications in residential as well as in the commercial sectors. In residential settings, they are used for cooking, water heating, space heating, and lighting. In commercial settings, they are commonly found in office buildings, educational institutes like schools, colleges, and universities, and healthcare buildings like hospitals [61]. Figure 2-3 shows the segment of micro-CHP market.

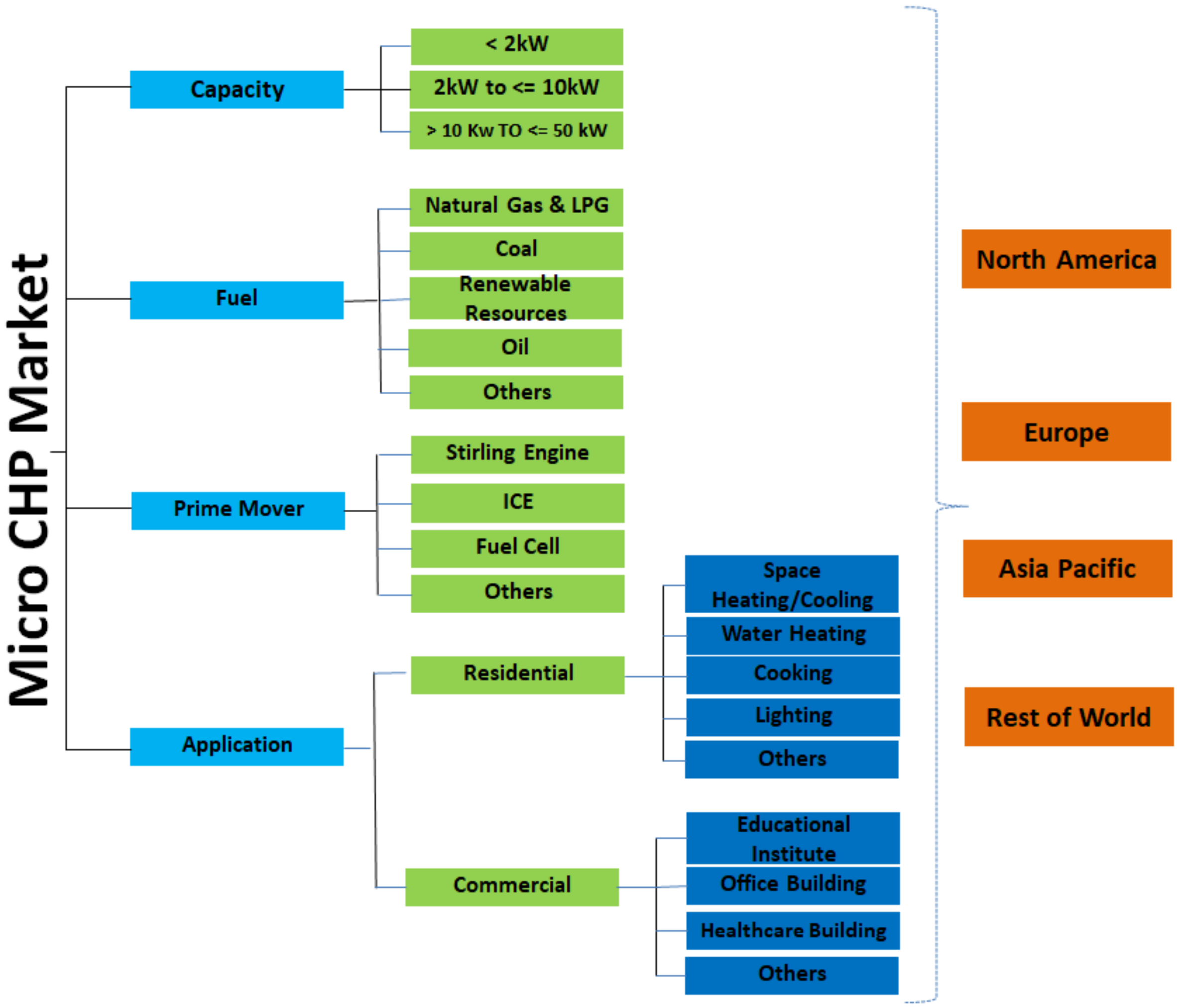

Figure 2-3: Micro-CHP market segment, adopted from [61]

1) By prime mover analysis

The market is divided into different categories, such as SE, ICE, FC, and others. Among these, the fuel cell segment is hoped-for to have a peak market share during the period of prediction. This is because of the numerous advantages it offers, including emissions-free, mute operation, and effective energy production. Additionally, FC innovation is experiencing the maximum Compound Annual Growth Rate (CAGR) across all segments. FC has the capability to reach net efficiencies ranging from 65 percent to 95 percent. As per the US Environment Protection Agency, wasted heat generated by FC could be effectively utilised for applications of household for domestic heating and water heating [9,62]. Figure 2-4 illustrates the global market proportion of micro-CHP systems in 2021 by prime movers.

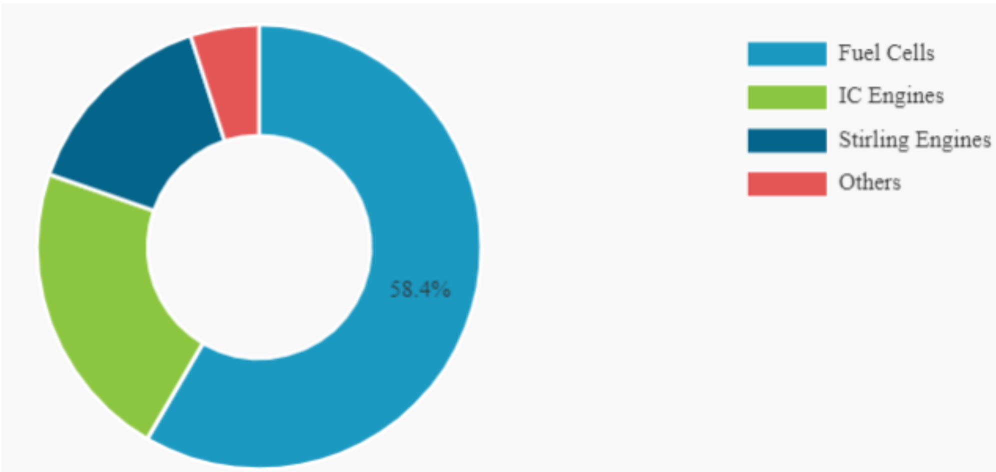

Figure 2-4: Worldwide micro-CHP market share in 2021, by prime movers [62]

In the residential micro-CHP market, the distribution of prime mover technologies differs by region and evolves over time. Traditionally, Stirling engines have been commonly used in domestic applications due to their reliability and suitability for small-scale heat and power generation [63].

However, as of 2023, ICE has captured the leading market share in the micro-CHP industry. Their dominance is primarily attributed to their efficiency, adaptability, and ability to cater to both residential and small commercial needs [64]. Additionally, projections for 2024 indicate that Stirling engines are expected to reclaim a leading position in the micro-CHP market, as their role in promoting energy efficiency and sustainability gains further recognition [65].

Recently, there has been a growing shift towards fuel cell systems in the domestic micro-CHP sector, primarily due to their superior electrical efficiency and lower emissions compared to ICE and Stirling engines. Forecasts suggest that by 2037, fuel cells will account for approximately 55% of the global micro-CHP market, driven by advancements in technology and their environmental benefits [63].

It is crucial to recognise that the uptake rates of different prime mover technologies in residential micro-CHP applications depend on factors such as regional energy policies, fuel availability, and technological developments. While fuel cells are projected to dominate the market in the upcoming years, Stirling engines and internal combustion engines are expected to maintain substantial market shares in specific regions and applications [63–65].

2) By capacity analysis

Categorised by power capability, the market is segmented into three segments: up to 2 kW, 2-10 kW, and 10-50 kW. The up to 2 kW section has been the dominant force in the market because of the growing installation objectives and the superior performance efficiency of micro-CHP systems for home use, in contrast to other power abilities. The growing adoption of greenhouse gas emission CHP systems in both commercial & residential frameworks will further drive the expansion of the worldwide market, particularly in the 2 kW capacity range [62].

3) By fuel analysis

Considering the type of fuels employed, the global market can be divided into categories such as NG, H_2, renewable resources, and others. The use of H_2 fuel is anticipated to experience significant growth due to its capacity to be rapidly generated from various sources and its potential for near-zero greenhouse gas emissions. The utilisation of H_2 has the potential to positively affect the environment and contribute to resolving the challenge of climate change [62].

4) By application analysis

By categorising the market based on usage, it can be divided into two sectors such as residential and commercial, encompassing various establishments like schools, malls, sports areas, houses, factories, shops, hospitals, and more. Household CHP units offer numerous advantages to users and customers, including environmental benefits, cost-effectiveness, energy savings benefits, comfort, and a reliable power source. Moreover, the residential segment is undergoing significant expansion due to variables like as the increasing need for heat and electricity, rapid urbanisation, and the growing adoption of low-carbon power generation, particularly in emerging markets [9,62].

5) By region analysis

The Asia-Pacific region dominates the micro-CHP market and is projected to retain its dominant position across the forecast period. Japan remains the most influential market player, while emerging economies such as China and South Korea are actively contributing to market growth. The increasing adoption of energy-efficient technologies that simultaneously generate heat and power, coupled with a focus on reliable energy solutions, is driving expansion in this region. The European market is anticipated to witness substantial growth in the coming years, supported by a well-established manufacturing, industrial, and automotive sector. The region's strong adherence to zero-emission building standards, coupled with a growing emphasis on low-carbon energy alternatives, is driving the uptake of micro-CHP systems. Furthermore, rigorous environmental directives implemented by European authorities—targeting a 20% boost in energy efficiency alongside a 20% reduction in greenhouse gas emissions—are hastening the shift towards cleaner, more efficient energy technologies. As a result, many European countries are adopting micro-CHP solutions to combat climate change and enhance energy sustainability. Although North America currently holds a smaller share of the micro-CHP market compared to Asia-Pacific and Europe, it is anticipated to have the fastest growth rate throughout the forecast period. This surge is driven by supportive government policies, rising interest in sustainable energy generation, and continuous advancements in energy-efficient technologies. Furthermore, increasing demand for peak power capacity across the grid and on-going innovations in CHP systems is projected to enhance the region's market prospects. In contrast, the rest of the World has a limited market presence due to slower technology adoption, lack of awareness, and substantial upfront capital requirements for domestic installations. However, certain countries, such as Brazil, Chile, and South Africa, are in the early stages of micro-CHP deployment, with on-going projects that may contribute to future market development. The capacity of micro-CHP systems to effectively integrate into existing heating systems, gas infrastructure, and electricity networks makes them a viable option for both residential and commercial sectors. As awareness and investment grow, these markets may gradually expand their adoption of micro-CHP technology [62].

2.1.3 The build-up of micro-CHP system for domestic use

Detailed information regarding the installation of micro-CHP units in household functions to meet the electrical & heat demands can be found in the provided references [66,67] and is shown in Figure 2-5. The micro-CHP unit is designed to be linked side by side to the grid in domestic homes to fulfil the electricity demand. In some houses where the maximum heat requirement is more than the maximum heat generation capability of the CHP system, an additional boiler is required to be installed to provide the extra heat. The overflow electricity produced by the micro-CHP system can be returned to the grid for sale, meanwhile, excess heat is stored in a thermal storage unit, as illustrated in Figure 2-5 [66].

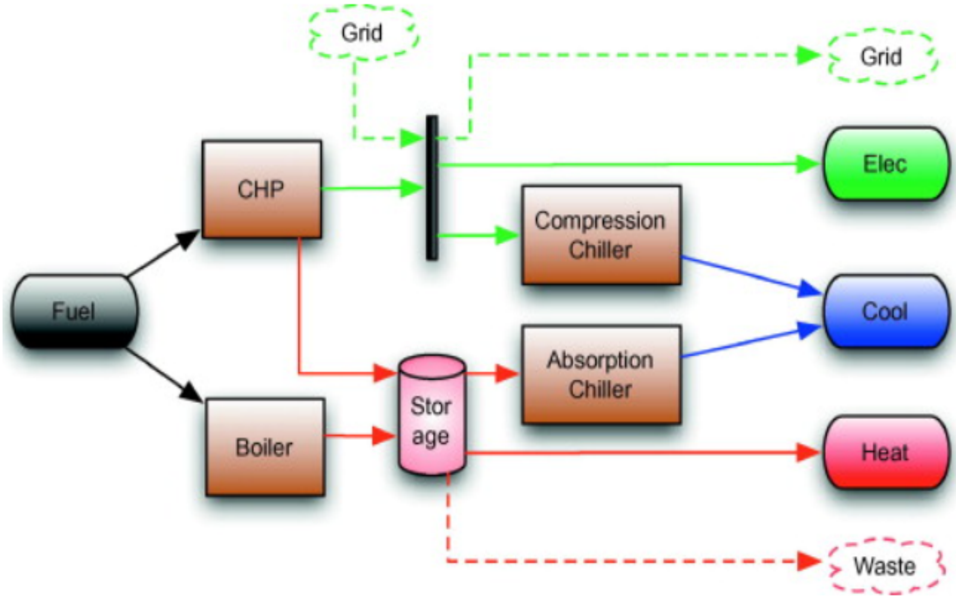

Figure 2-5: The energy flow diagram of micro-CHP for household application [66]

2.1.4 Optimal energy distribution algorithm

This algorithm aims to generate control signals for the CHP components to maximise cost-efficiency. Figure 2-6 displays a flowchart of the energy dispatch strategy. The algorithm incorporates fuel and electricity pricing as its primary input parameters. In formulating the Linear Programming (LP) model, the following assumptions have been established:

- The building's total electrical, cooling, and heating energy demands are met by optimally utilising all available energy sources.
- The CHP system adheres to the energy conservation principle, where the total energy demand equals the energy supplied minus the energy losses within the system [68].

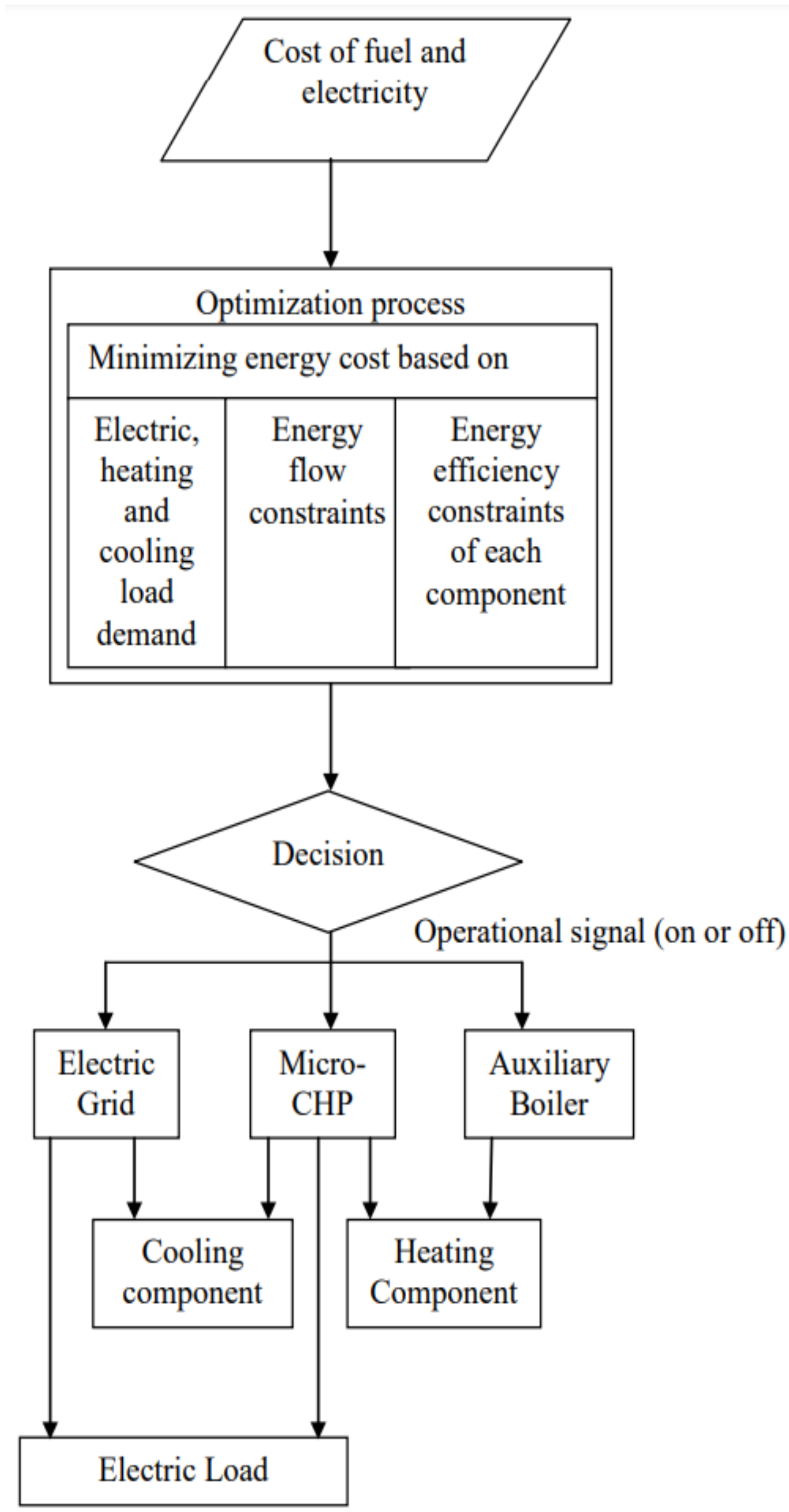

Figure 2-6: The ideal energy flow diagram of the dispatch algorithm [68]

Wide-ranging explanations on the network flow model and its optimisation approach are provided in the upcoming sections.

1) Overview of the Network Flow Model

Network flow models are widely utilised to formulate linear programming problems [69]. In this study, a network flow representation of a standard CHP system has been formulated based on the schematic shown in Figure 2-5. The key benefits of employing a network flow model in energy system analysis are its ability to clearly represent energy flow, supply-demand relationships, and efficiency limitations. Additionally, this model simplifies the formulation of the objective function and associated constraints within the LP framework. The network flow model corresponding to a representative CHP configuration is illustrated in Figure 2-7, where nodes represent energy sources and demand points, while arcs indicate energy flow pathways. Nodes 1 and 13 serve as “conceptual” nodes symbolising the system's total energy requirement, which comprises the sum of electricity, cooling, and heating demands. Similarly, Node 12 is a conceptual node representing system energy losses [68].

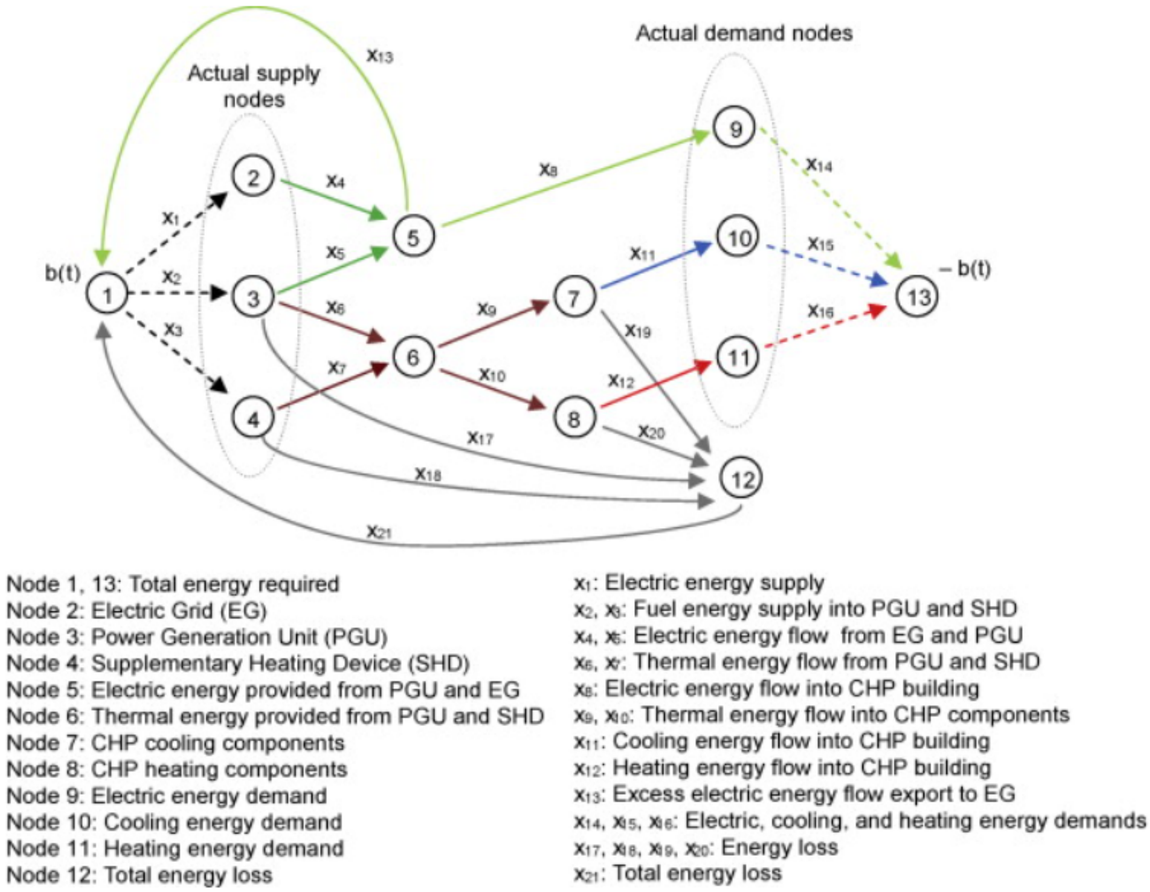

Figure 2-7: Network flow representation of a standard CHP system [68]

2) Optimising strategy

The following section outlines the formulation of the goal function and the associated flow network model. The main aim of this approach is to minimise the overall operating expenses of the CHP system across a period of T(s), while ensuring that the total energy requirements are satisfied. The objective function is formulated as follows [67,68].

$$Minimise\ \{z(x)\}=\sum_{t=1}^{T}\{c_1(t)x_1(t) + c_2(t)x_2(t) + c_3(t)x_3(t) - c_4(t)x_{13}(t)\} \quad \text{Equation 2-2}$$

Where $x_1(t)$, $x_2(t)$, and $x_3(t)$ represent the share of energy sourced from the electric grid (EG), the power generation unit (PGU), and the supplementary heating device (SHD), respectively, during the time step t, where t = 1, 2, …, T, and time is measured in seconds (s),. The cost parameters $c_1(t)$, $c_2(t)$, and $c_3(t)$ correspond to the price of purchasing 1 kWh of electricity from the grid, the fuel cost for generating 1 kWh in the PGU, and the cost of fuel for producing 1 kWh in the SHD, respectively. Furthermore, x13(t) signifies the electricity exported back to the grid during period t, with $c_4(t)$ being the feed-in tariff or selling price per kWh.

It is assumed that any surplus energy must be sold back to the grid within the same time period and cannot be stored for future use, meaning there is no interdependence between variables across different time periods. Consequently, there is no interdependence of variables between different periods, allowing the problem to be broken down and analysed independently for each period. The model determines the optimal energy allocation from each source to minimise the total operational cost.

Equation 2-3 to Equation 2-15 defines the constraints governing the flow of energy. These constraints ensure energy conservation at each node by requiring that the total incoming energy equals the total of the energy demand and the outgoing energy at that node.

$$x_1(t)+x_2(t)+x_3(t) - x_{13}(t)-x_{21}(t) = b(t) \quad \text{Equation 2-3}$$

$$x_4(t) - x_1(t)=0 \quad \text{Equation 2-4}$$

$$x_5(t) + x_6(t) + x_{17}(t)-x_2(t) = 0 \quad \text{Equation 2-5}$$

$$x_7(t) + x_{18}(t)-x_3(t) = 0 \quad \text{Equation 2-6}$$

$$x_8(t) + x_{13}(t) - x_4(t) - x_5(t) = 0 \quad \text{Equation 2-7}$$

$$x_9(t)+x_{10}(t) - x_6(t) - x_7(t) = 0 \quad \text{Equation 2-8}$$

$$x_{11}(t) + x_{19}(t) - x_9(t) = 0 \quad \text{Equation 2-9}$$

$$x_{12}(t) + x_{20}(t) - x_{10}(t) = 0 \quad \text{Equation 2-10}$$

$$x_{14}(t) - x_8(t) = 0 \quad \text{Equation 2-11}$$

$$x_{15}(t) - x_{11}(t) = 0 \quad \text{Equation 2-12}$$

$$x_{16}(t) - x_{12}(t) = 0 \quad \text{Equation 2-13}$$

$$x_{21}(t)-x_{17}(t)-x_{18}(t)-x_{19}(t)-x_{20}(t) = 0 \quad \text{Equation 2-14}$$

$$x_{14}(t)+x_{15}(t)+x_{16}(t) = b(t) \quad \text{Equation 2-15}$$

As illustrated in Equation 2-3, the total energy demand of the system, b(t), is the sum of the energy acquired from the electric grid ($x_1(t)$) and provided to the power generation unit ($x_2(t)$) and the space heating device ($x_3(t)$), minus the energy returned to the grid ($x_{13}(t)$) and the energy lost ($x_{21}(t)$). It is important to note that b(t) represents the anticipated electrical, cooling, and heating requirements at a specific time step. Equation 2-16 and Equation 2-17 demonstrate the energy conversion characteristics of the PGU. Specifically, from the total input energy $x_2(t)$, a fraction a_1x100% is converted to electricity, a_2x100% is converted to thermal energy, and the remainder $(1-a_1-a_2)$ x100% is lost.

$$x_5(t) - a_1 \,.\, x_2(t) = 0 \qquad \text{Equation 2-16}$$

$$x_6(t) - a_2 \,.\, x_2(t) = 0 \qquad \text{Equation 2-17}$$

Equation 2-18 illustrates that, for the SHDs, a fraction a_3x100% of the energy input $x_3(t)$ is converted into thermal energy, with the remaining $(1-a_3)$ ×100% lost.

$$x_7(t) - a_3 \,.\, x_3(t) = 0 \qquad \text{Equation 2-18}$$

Equation 2-19 addresses the cooling subsystem of the CHP setup, where only a_4x100% of the energy input $x_9(t)$ contributes to usable cooling output and $(1-a_4)$ x100% is lost.

$$x_{11}(t) - a_4 \,.\, x_9(t) = 0 \qquad \text{Equation 2-19}$$

Equation 2-20 demonstrates that for the heating component, a_5x100% of the input energy $x_{10}(t)$ is effectively utilised, while the remaining $(1-a_5)$ x100% is considered waste.

$$x_{12}(t) - a_5 \,.\, x_{10}(t) = 0 \qquad \text{Equation 2-20}$$

The decision variables $x_2(t)$ and $x_3(t)$ are subject to upper limits, which are determined by the maximum energy output capacity of the PGUs and SHDs for each time period. These upper bounds represent the highest amount of energy these units can produce. In contrast, there are no such limits on the amount of electricity that can be procured from the electric grid.

Furthermore, the lower bounds for variables $x_{14}(t)$, $x_{15}(t)$, and $x_{16}(t)$ are determined by the respective energy demands (electric, cooling, and heating energy), which are dictated by the specific energy demands at time t. When the electricity demand is zero, both the lower and upper bounds of the corresponding variable are set to zero, indicating no energy is required or supplied during that interval. For all other variables, the bounds are flexible, provided they remain positive [68].

2.1.5 Difference between the conventional power plant and a CHP plant

In a conventional power plant, electricity generation follows an inherently inefficient process. Fossil fuels like coal, oil, or natural gas are burned in a large furnace to produce thermal energy. This heat converts water into steam, which then power a turbine connected to a generator, ultimately producing electricity. However, significant energy losses occur at each stage of this process, with much of the heat energy being wasted as a by-product. In contrast, a CHP plant not only generates electricity but also captures and utilises the waste heat for heating purposes, such as supplying hot water to consumers. This approach, known as cogeneration or CHP, allows for the concurrent generation of electricity and useful thermal energy, thereby substantially improving overall energy efficiency [70]. Figure 2-8 shows the comparison of the conventional power plant and the CHP plant.

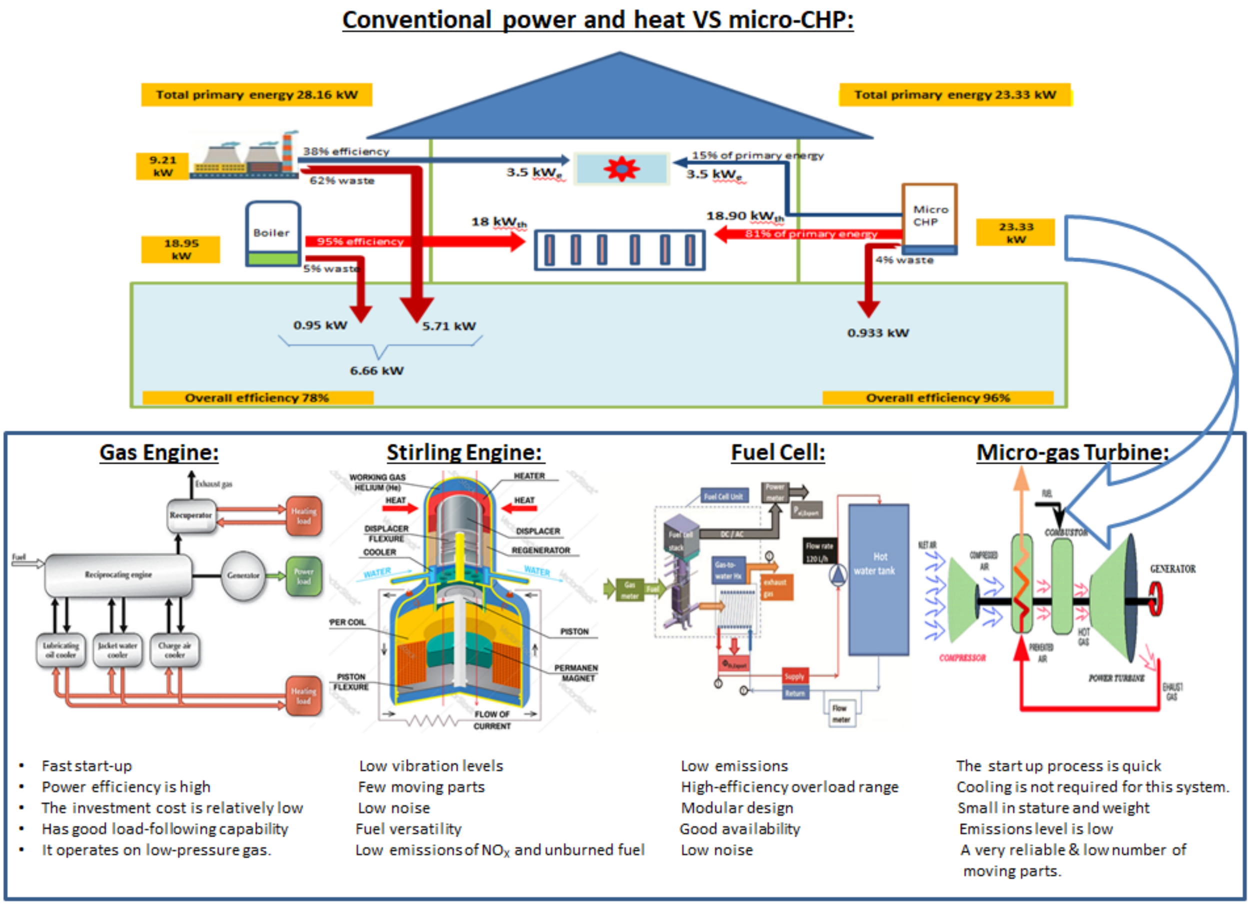

Figure 2-8: Conventional power and heat VS micro-CHP generation, adopted from [9,71–73]

The diagrams above clearly demonstrate that the system of CHP is more remarkably efficient, resulting in much less energy wastage compared to conventional power plants.

2.1.6 Basic elements of the micro-CHP system:

Three key components are integral to most micro-CHP technologies: the prime mover, which serves as the engine generating mechanical power, the electricity generator, & the heat recovery unit [52]. The fundamental elements of a micro-CHP system are depicted in Figure 2-9.

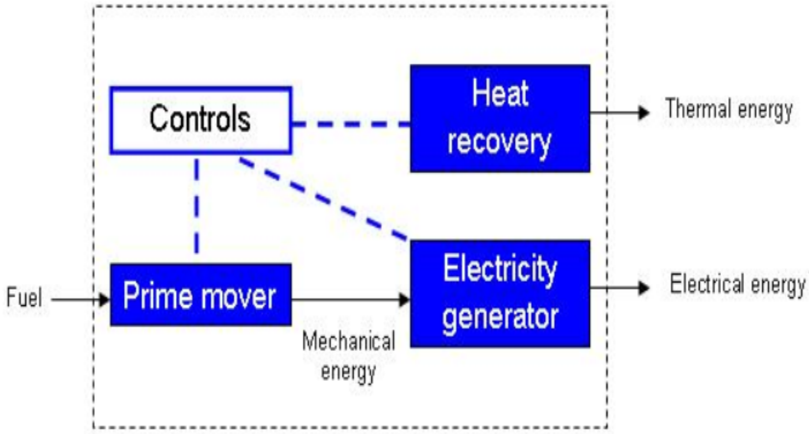

Figure 2-9: Elements of a micro-CHP plant [74]

1) Prime movers

The prime mover stands as a fundamental and crucial component of a micro-CHP system [75]. This refers to the engine that is used to generate mechanical power [76]. There are various types of prime movers, including ORC, MGT, steam engines, ICE, FC, and SE [12,77]. Selecting the appropriate prime mover of the correct size is a critical element in any cogeneration system, as it drives the overall functioning of the system. When researching prime movers for your cogeneration facility, several important factors should be considered [78]:

- The required electrical output.
- The necessary heat level often referred to as the 'grade' of heat, which depends on temperature.
- The heat-to-power ratio, indicating the balance between recoverable thermal energy and electrical generation.
- The availability of different fuel types.
- In waste heat recovery systems, evaluating the temperature level of the waste heat must be assessed.
- The nature of the thermal load (e.g., steam, hot water, or chilled water) and its specific pressure and temperature conditions.

Beyond these technical aspects, additional considerations include:

- Acceptable noise levels in the surrounding environment.

- The allocated space for the primary engine.
- Emission levels and regulatory compliance.
- Maintenance requirements and responsibilities.
- System reliability and the consistency of maintenance schedules.
- The ability to modulate power output, both electrical and thermal [78].

2) Heat recovery unit

This device harnesses the remaining heat produced during the generation process and utilises it effectively. There are two primary purposes for utilising this heat:

- Heating
- Steam

In steam turbine configurations, thermal energy is employed directly, typically following a reduction in steam pressure. Conversely, gas turbine setups recover heat through a steam generator, which is generally available in two primary variants: a standard heat recovery steam generator (HRSG) and a fired HRSG. The fired version incorporates additional fuel combustion to boost thermal efficiency. In micro-CHP units and combustion engine-based systems, the recovered heat is conveyed to water and is utilised for heating purposes using simple heat plate exchangers [60,79].

3) Electricity generator

Generators can be classified into two primary types.

- Self-controlled
- Grid-controlled

Grid-controlled generators utilise a control apparatus to oversee the grid's condition. In the event of a power loss, these generators will automatically shut down, making them unsuitable for standby power generation. For applications below the 100k output range, using grid-controlled generators could lead to a substantial rise in costs. Therefore, self-controlled generators are typically preferred. Self-controlled generators are mainly employed for backup functions or in regions lacking grid-supplied electricity. They function in what; is termed "island mode" during grid failures, ensuring that electricity is not fed back into the grid, which could endanger workers conducting repairs [79,80].

2.1.7 Operations strategies in micro-CHP systems

To efficiently control both the thermal & electrical output of a micro-CHP system, it is important to consider that peak times for electrical demand and heat demand may not align. However, the heat-to-power ratio in micro-CHP systems stays consistent. Hence, implementing an operational strategy becomes essential to regulate both the electrical & thermal output of the system. Various strategies of operation can be employed to achieve this goal as follows below [66].

1) Following the heat demand

The residential unit CHP system is operated to align with the heat requirements. Any extra electricity generated by the CHP system is exported to the power grid for sale, while any shortfall in electricity consumption is supplemented by sourcing electricity from the grid [66].

2) Following the electricity demand

The residential unit's electric demand is managed by the CHP system. The heat load is fulfilled by either generating additional heat through the auxiliary boiler could be utilised, or the surplus heat generated by the CHP system can be effectively managed [66].

3) Continuous operation

The CHP system runs for a set duration regardless of the energy requirements, a tactic employed for certain engines that cannot function efficiently under partial load conditions [66].

4) Peak shaving

The CHP system is designed to manage a specific portion of the electricity demand throughout periods of high electricity usage. By implementing this strategy, users can effectively decrease their reliance on grid power during peak load conditions. This approach proves particularly beneficial when utility companies impose higher rates for electricity consumption during peak load periods [66].

5) Base load operation

The CHP system is designed to meet the primary energy needs of the household, with any surplus electricity needed to be procured from the grid [66].

6) Aggregate load control (ALC)

According to citation [81] the introduction of micro-CHP systems in individual households holds the potential to yield economic advantages and mitigate carbon emissions at the household scale. However, the widespread adoption of micro-CHP systems into the local grid can introduce challenges, such as an uncertain burden on the grid infrastructure. Consequently, this may result in financial losses for the utility company and an overall increase in carbon emissions due to the idle operation of the generator that powers the grid. To address this issue, reference [81] recommends the implementation of an advanced load control mechanism for all micro-CHP systems that are interconnected with the power grid. The formula provided below can be employed to ascertain the quantity of operational CHP systems within the power grid, under the assumption that they are all of equal dimensions:

$$\mathrm{N} = \frac{E-Pa}{Poe} \qquad \text{Equation 2-21}$$

In the equation, ''N'' represents the number of activated micro-CHP units within the local grid, ''E (kWh)'' represents the combined electrical consumption on the local grid in kilowatts, ''Pa (W)'' represents the combined load threshold, triggering the activation of multiple micro-CHP units, and ''Poe (W)'' represents the electrical power rating of each micro-CHP unit. Within the ALC control framework, priority is given to activating the micro-CHP system in the house when grid conditions permit meeting the thermal load. However, it is crucial to emphasise that using ALC may not always fully meet the heat requirements in the involved residences, in which case an auxiliary boiler will be used to meet the extra thermal demand. Additionally, there may be situations under ALC where some houses may experience wasted thermal energy to meet the electric demand of the grid [81].

2.1.8 Future of micro-CHP system:

The micro-CHP market has shown significant growth in the past few years. In 2021, its size had reached 3.62B in USD, & it is expected to continue expanding. By 2029, it is estimated to reach a value of USD 8.16 billion, with a compound yearly growth rate (CAGR) of 11.0% throughout the projected timeframe. However, need to note that the worldwide pandemic of COVID-19 has had a notable impact on the market, leading to lower demand worldwide compared to the levels of pre-pandemic [82]. In 2021, the market saw a modest growth of 5.4% [62].

2.2 Critical discussion / Comparison of the four major Prime Movers

This section delved into a wide-ranging critical discussion of four major prime movers, including the Internal combustion engine (ICE), Fuel cell (FC), Stirling engine (SE), & Micro-gas turbine (MGT). It provided detailed insights into each prime mover's introduction, historical background, constituent components, various types, applications across different sectors, inherent characteristics, current state-of-the-art technologies, fuel adaptability, key manufacturers, market analysis, prospects in the industry, benefits, limitations, and anticipated advancements.

2.2.1 Internal combustion engines (ICE)

ICE is also known as reciprocating gas engines, gas engines (GE), or piston engines. These engines are a mature and extensively used technology for power generation in both industrial and residential sectors, particularly in CHP systems. ICE offers high part-load efficiency, rapid start up, strong reliability, and effective load-following capabilities [83]. Figure 2-10 shows a schematic representation of an ICE within a micro-CHP system.

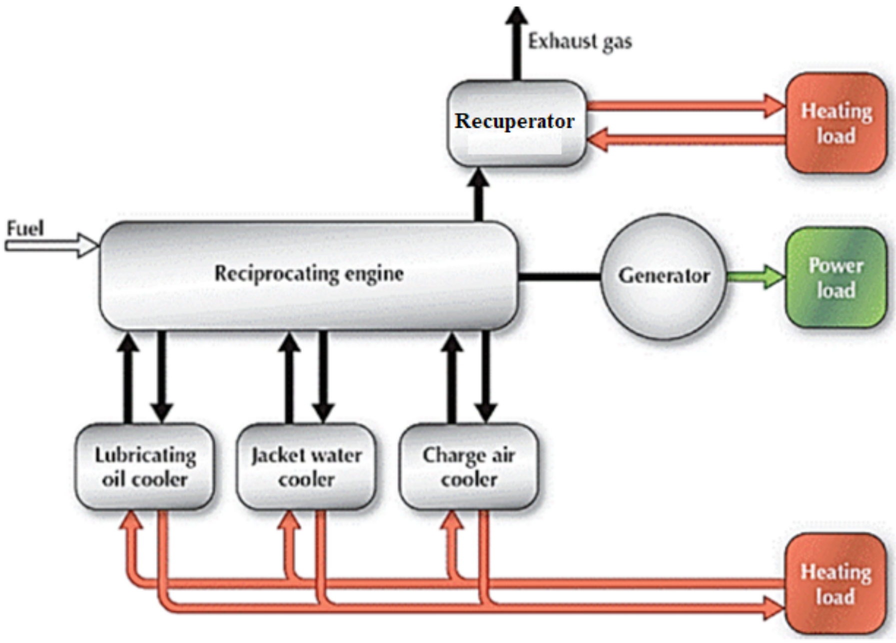

Figure 2-10: Schematic of an Internal combustion engine [72]

In ICE, the fuel is ignited within the cylinder, causing the hot combustion gas to generate movement in the piston. This movement is subsequently transmitted to the crankshaft, which powers external devices. ICEs fall into two categories: those that run on gasoline using the Otto cycle & those that run on diesel using the Diesel cycle. Gasoline engines are sparked by an electric spark and have a lower combustion temperature, resulting in lower efficiency. However, they are quieter compared to diesel engines. In contrast, diesel engines ignite because of the high temperature reached by compressing the diesel mist/air mixture in the cylinder. Their higher compression ratio leads to increased combustion temperatures and improved thermal efficiency. Diesel engines are generally heavier than their gasoline counterparts with equivalent power output and are typically used in heavy-duty sectors such as trucking and marine transport, although certain smaller passenger vehicles also adopt diesel technology. For micro-CHP applications, internal combustion engines (ICE) are ideally fuelled by natural gas or heating oil. Gasoline-powered ICEs are like NG engines, while engines powered by heating oil essentially function as diesel engines, as home heating oil is quite similar in composition to diesel oil. Therefore, the conversation of the engine mentioned here is relevant to the ICE used for the micro-CHP system [60].

The difference between an ICE and a conventional gas engine is that an ICE uses the produced heat to fulfil the requirement for thermal energy while the conventional gas engine does not. ICE is available in the market with its different characteristics [84].

1) Brief history of ICE

The first ICE, as understand it today, was invented by Robert Street and patented in England in 1794. Street's engine involved heating the base of a cylinder, with fire, & injecting a little amount of tar or turpentine into the heated section, creating vapour. As the piston rose, it drew in air to create the explosive mixture and a flame for ignition. Later, Lenoir employed this process in the initial engine that achieved commercial success. In approximately 1800, Phillippe Lebon obtained a patent in France for an engine that made use of compressed air, compressed gas, and electricity to initiate combustion. Samuel Brown's engine, which gained recognition in the early 19th century, did not bring about significant advancements in engine technology. This could be ascribed to the reality that Brown's engine relied on the older ideas of Huygens, rather than the more advanced ideas put forth by Street. The success of atmospheric steam engines during this time likely influenced the design choices made by Brown. The engine developed by Brown comprised substantial chambers where hot gases from flames were cooled by injecting water, thereby creating a partial vacuum. The operational pistons, located in cylinders neighbouring to the substantial chambers, were actuated by atmospheric pressure and linked to the same crankshaft. It is crucial to emphasise that combustion didn’t occur within the operational cylinder, Brown's engine cannot be considered an ICE in the traditional manner. Despite this limitation, Brown was a determined inventor and his engines found use in various applications such as pumping, as well as powering carriages and boats. In 1833, W. L. Wright patented an engine in England that represented significant design advancement. This engine featured separate pumps for supplying gas and air to an operational cylinder. The charge was held in spherical bulbs located close to the cylinder ends, and ignition took place as the piston reached the culmination of its stroke. The engine operated in double acting and had a water jacket, a fly-ball governor, & poppet exhaust valves. However, there are no known records of its performance, despite its promising design features [85,86].

In 1838, William Barnett obtained a patent in England for an engine that was an improvement on previous models in the country. This engine compressed the gas and air independently, igniting the fuel-air mixture as the piston reached the end of its stroke [85,86].

The hot-tube method of ignition, initially patented in America by Drake and subsequently patented in England by Newton in 1855, was later replaced with electric ignition. The Barsanti-Matteucci engine, patented in 1857, is noteworthy as it was the first machine to achieve commercial success, although its Italian inventors did not benefit from it. It operated by exploding gas and air under the piston, propelling it upwards until all the energy from the explosion was utilised. The piston then descended under atmospheric pressure to perform the work [85,86].

Lenoir of France obtained the patent for the first engine to gain significant adoption in 1860. It bore a resemblance to a double-acting steam engine and featured a slide valve for both intake and exhaust functions. The Lenoir engine allowed gas and air to enter during a portion of the stroke, followed by an explosion and expansion. It is important to mention that all these engines operated without compression. In 1860, Beau de Rochas outlined the necessary principles aimed at improving the efficiency of ICE:

- The cylinder with the largest volume for a given surface area.
- Maximum speed of movement.
- Maximum potential growth.
- Maximum pressure at the start of the expansion phase

Beau de Rochas also outlined the four motions that compose the cycle of the four-stroke engine [85].

The most intriguing aspect of the advancement of ICE for Americans is the role played by Brayton around 1872 to 1874. The Brayton engine can be considered a precursor to the modern Diesel engine. The combination of gas & air combusted at a consistent pressure resulted in a diagram like that of a steam engine. Although this engine was produced for a period, it couldn’t rival the efficiency of the Otto-Langen free-piston engine. It was engineered to run on both gas and petroleum [85,87].

Dr. Nicholas Otto, a German inventor, created the famous Otto engine, which was patented in 1877. This engine operates on the four-cycle or Otto cycle, which was originally described by Beau de Rochas. The Diesel engine for oil was developed around 1894. This engine resembles the Brayton engine, where air is pressurised to a pressure of approximately 500 pounds, & oil is injected into the pressurised air. The oil undergoes spontaneous combustion at a relatively consistent pressure, leading to subsequently resulting in a prolonged expansion. The elevated temperature of the air before fuel injection, along with the elevated temperature sustained during the injection process and the prolonged expansion, make the Diesel engine the most efficient thermal motor. The Diesel engine has been recently developed and is now being manufactured in Europe and America. Many American manufacturers are adopting the features of the Diesel engine in their new engines [85,86,88,89].

2) ICE components

Below are the common parts of an ICE:

a) Cylinder

Cylinders are distinguished by two key dimensions: the bore and stroke. The bore refers to the internal diameter of the cylinder, while the stroke represents the distance of the piston's movement as it reciprocates between the Top Dead Centre (TDC) and Bottom Dead Centre (BDC) during each cycle. TDC & BDC mark the highest and lowest points of the piston's stroke. The cylinder block also includes empty areas surrounding and between the cylinders, which are called jackets. These hollow sections allow coolant to flow in and circulate, ensuring efficient cooling in liquid-cooled engines [3,90].

b) Piston

The piston is a cylindrical component that moves vertically within the cylinder. This movement enables the entire combustion cycle to occur, including intake, compression, combustion, and exhaust. To understand this procedure in detail, please refer to the explanation below. The piston's diameter is slightly smaller than the cylinder bore to prevent the piston surface from wearing out quickly. There are three piston rings placed in circular grooves on the piston's surface. The aluminium rings establish direct contact with the cylinder liner, thereby providing a protective barrier for the piston against wear. The initial two rings serve as compression rings, featuring an outer chamfered section that effectively inhibits the ingress of waste gases into the crankcase. Conversely, the third ring, commonly referred to as the oil ring, functions to prevent the infiltration of oil into the combustion chamber & guarantees the appropriate desperation of oil along the walls of the cylinder [90–92].

c) Crankshaft

These components in the engine assist in transforming the linear (back-and-forth) motion of the piston into rotational movement, a function achieved through the connecting rod. Located beneath the cylinder block, they are housed within a casing known as the crankcase. The crankshaft, which performs this conversion, features offset sections called crankpins that serve as attachment points for the connecting rods—one for each cylinder in multi-cylinder engines. Crankshafts can be manufactured either as assembled units or forged in a single piece, with the latter being preferable due to reduced vibration, better structural integrity, and enhanced stress-handling capacity. Typically, crankshafts are produced from steel via casting or roll forging. Single-piece designs are usually made from heat-treated carbon steels, although alternative materials like vanadium micro-alloyed steels are also used for their high strength and the advantage of eliminating the need for post-processing heat treatment [90–92].

d) Connecting rod

The components of these types of engines are used to link the piston and the crankshaft together. As previously earlier, they convert the back-and-forth motion of the piston into the rotational motion of the crankshaft. One end of these components is connected to the piston using a piston pin, also referred to as a gudgeon pin or wrist pin. In the assembly of the crankshaft, the opposite extremity is affixed to the crankpin journal through the utilisation of bolts, thereby ensuring the stability of the upper and lower bearing caps, commonly referred to as the big end. The big end connecting rod is responsible for inserting two half-shells into the crank journal, thereby constituting the bearing. Neither end is rigidly fixed, allowing them to rotate within a certain range. As a result, both ends are in constant movement & experience significant stress from the pressure exerted by the piston. The connecting rod is typically crafted of forged steel, although occasionally it is constructed from aluminium alloy to prioritise lightweight and high-impact absorption capabilities. Due to its critical role and susceptibility to failure, the connecting rod is produced with a high level of precision [90,93].

e) Cylinder head

These components of the engine function as a protective layer for the cylinder block, rocker arms, valve, and ignition element. They are attached to the cylinder block using a head gasket. The head of the cylinder is typically constructed from cast iron, but in certain cases, aluminium alloy is used to reduce weight and enhance heat conductivity compared to cast iron [90,93].

f) Camshaft

This component of the ICE is a shaft that houses a cam. Its primary purpose is to directly control the valves by either sitting directly on top of them or using a rocker arm and pushrod mechanism. The timing of the valves is dictated by the dimensions of the camshaft. In other words, the camshaft, which is linked to the crankshaft both directly via a reduction gear or indirectly via a pulley & timing belt, dictates when the valves open and close. The camshaft, which is connected to the crankshaft via a gear, necessitates the use of a pushrod & tappet mechanism in conjunction with rocker arms. Typically, camshafts are constructed using chilled iron castings or billet steel for superior quality. The inclusion of chilled iron provides enhanced durability and surface hardness, resulting in increased resistance to wear [90,91,93].

g) Valves

Valves, also referred to as poppet valves in ICE, consist of a valve stem, a long, slender circular rod, and a valve head, a flat circular disk that tapers along the rod. Their primary purpose is to facilitate the fuel & air intake, & the release of exhaust gases. The valve's opening & closing are controlled by the sliding motion of the camshaft & its related mechanisms. Engine valves are crafted using steel alloys that are infused with sodium to enhance their ability to transfer heat. These valves are categorised into two types: the inlet or intake valve, which permits the entry of fresh charge into the chamber when open, & the outlet or exhaust valve, which facilitates the release of exhaust gases [90,93].

h) Rocker arm

This component of the ICE has a crucial function in transferring the rotational movement of the cam or crankshaft. It does so by using a tappet or latches to convert it into a rectilinear motion of the valve stem. This action assists in pushing down the head of the valve. The rocker arm for light and medium-duty engines is constructed using steel stampings. On the other hand, the heavy-duty diesel engine rocker arm is crafted from cast iron & forged carbon steel, providing enhanced strength and stiffness. The rocker arms move back and forth around a stationary pivot rod located in the cylinder head [90].

i) Crankcase

These components of the ICE are situated beneath the cylinder block, which accommodates the rotating crankshaft bearings. The main bearing is a sliding bearing that is adequately lubricated with oil. It is typically common to find three bearings located in the crankcase of four-cylinder inline petrol engines, with one positioned at each end and another in the middle. In contrast, diesel engines typically have five main bearings, with one positioned at each end and one located between each cylinder. The crankcase is constructed from a combination of cast iron and aluminium, mirroring the materials utilised for the cylinder block. The crankcase performs multiple functions for the engine, including protecting its internal mechanisms from dust, dirt, and other substances. Additionally, it acts as a container for the crankshaft & connecting rod, ensuring the presence of oil and air [3,90].

j) Oil pump and sump

The oil pump's purpose is to circulate oil throughout the engine, ensuring that it is properly lubricated, cleaned, and cooled. The oil pump is powered by the gear connected to the crankshaft. By pressurising the oil, it is able to reach different components of the engine, providing lubrication & cooling to the system. The oil sump functions as a storage tank that holds oil. This oil is drawn out by the oil pump and passes through a strainer to prevent any dirt or debris from entering the engine. Before being distributed to the various parts of the engine, the oil goes through the oil filter and oil cooler. After completing its task, the oil returns to the oil sump [3,90].

3) ICE types

Currently, two main types of internal combustion engines (ICE) are widely used: spark ignition (SI) gasoline engines and compression ignition (CI) diesel engines. Both generally function through a four-stroke cycle consisting of intake, compression, combustion, and exhaust phases.

The primary distinction between SI and CI engines lies in their fuel introduction and ignition methods. In SI engines, a mixture of air and fuel is drawn into the cylinder during the intake stroke. After compression, a spark plug ignites the mixture, producing a high-pressure explosion that drives the piston downward. CI engines, such as diesels, function differently—they intake only air, which is then compressed to an extremely high temperature. At the completion of the compression stroke, fuel is directly injected into the hot, pressurised air and ignites on contact, eliminating the need for a spark plug [94]. Figure 2-11 illustrates the ignition method of Spark ignition and compressed ignition engines.

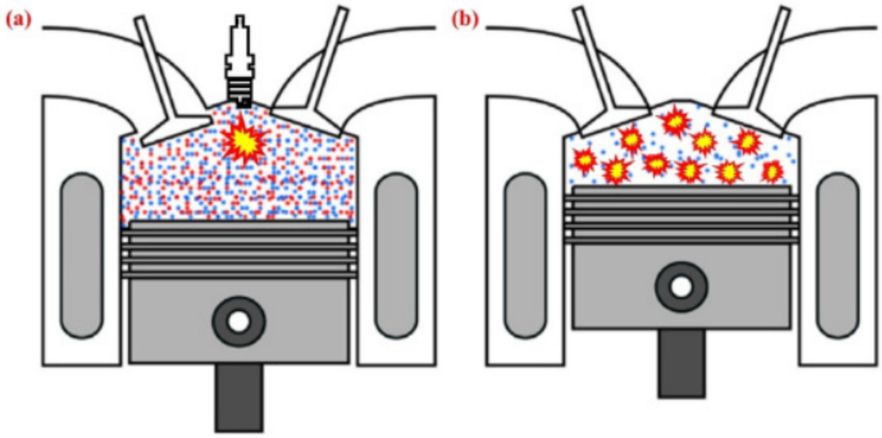

Figure 2-11: Ignition method: (a) Spark Ignition and (b) Compression Ignition [95]

4) Application and the characteristics

Below are the key applications and characteristics of an Internal Combustion Engine, highlighting its versatility across various sectors and its fundamental operational features.

a) Applications

ICE is aptly tailored for a multitude of distributed generation tasks and finds widespread utilisation in power generation and CHP systems across commercial, industrial, & institutional facilities. These engines boast rapid start-up times, efficient load management, impressive part load efficiencies, and robust reliability. Employing multiple ICE units in many instances can augment the overall capacity and operational readiness of the plant even further. Compared to gas turbines of similar size, ICEs have higher electrical efficiencies, resulting in reduced fuel-related operating expenses. Moreover, for capacities below 20 MW, the initial investment for ICE gensets tends to be lower compared to gas turbine gensets. Although the maintenance expenses for ICE are typically higher compared to gas turbines, they can frequently be managed by in-house staff or local service providers [96].

- *Combined heat and power*

In the USA, there are more than 2,000 active CHP installations that uses ICE. These installations have a total power capacity of approximately 2.3 gigawatts [97]. Many of these systems use spark ignition engines powered by NG or alternative gaseous fuels such as biogas or landfill gas. NG is a cheaper fuel option compared to petroleum-based fuels, and using gaseous fuels generally results in more effective emissions control. ICE-based CHP systems are commonly found in various types of facilities, including water treatment plants, hospitals, universities, industrial sites, and both commercial and residential buildings. The size of these facilities can vary widely, ranging from 1 kW to over 18 MW, with larger facilities often consisting of multiple units. Approximately 84 percent of the overall capacity in ICE-based CHP systems is comprised of spark-ignited engines powered by natural gas or alternative gaseous fuels [59,96].

CHP systems utilising engines are most suitable for providing space heating and hot water in commercial and institutional buildings. Meeting hot water demand is usually the simplest thermal requirement to fulfil. CHP is commonly used in buildings with high and simultaneous demand for electricity and hot water, including colleges, hospitals, residential complexes, and hotels. Additionally, office buildings, warehouses, & service applications can also benefit from CHP, particularly if there is a need for space heating. The development of heat-activated cooling technologies and thermally regenerated desiccant systems has the potential to enhance the utilisation of engine-based CHP systems, particularly by elevating thermal energy demand in specific building categories. Utilising the thermal output from CHP units for absorption-based cooling and desiccant-based dehumidification has the potential to enhance the scalability and cost-effectiveness of CHP systems across various sectors, including residential buildings, schools, colleges, hotels, restaurants, and hospitals. Additionally, the application of advanced technologies can be applied to sectors like eateries, grocery stores, and cold storage facilities, providing a fundamental thermal demand that makes these sectors suitable for the implementation of CHP systems [96].

- *Emergency/Standby generators*

ICE emergency/standby generators find application in diverse environments, encompassing residential dwellings, medical facilities, telecommunication infrastructure, data centres, scientific research laboratories, and contemporary naval vessels. In domestic contexts, these arrangements may manifest as either portable spark-ignition engines powered by gasoline or as fixed installations fuelled by natural gas or propane. On the other hand, commercial and industrial setups typically rely on diesel engines. Diesel engines offer several advantages for standby applications, including lower initial costs, the capability to stockpile fuel on-site for unforeseen situations, and swift initiation and escalation to full load. However, due to their higher emissions levels of air pollutants, these diesel systems typically face limitations regarding the duration of sustained operation. Additionally, their capacity to offer additional services, such as peak shaving, may be limited due to the constraints imposed by permits [96].

- *Peak shaving*

Engine generators can be used to provide power during times when the demand for electricity is highest. This benefit extends to both the end-users and the local utility companies alike. These potential advantages include lower expenses on peak power tariffs for the facility, while the utility can improve its efficiency and reduce the need for additional investments in power transmission, generation, and distribution, which are typically utilised for only a small number of hours annually (0-200). In a conventional peak-shaving initiative, the utility may request the facility to operate its own generator during peak demand periods, and as compensation, the facility will receive monthly payments from the utility [96].

b) Characteristics

Table 2-1 shows the characteristics of the ICE engines.

Table 2-1: Internal combustion engine characteristics

Characteristic	**ICE engine**	**Characteristic**	**ICE engine**
Electric efficiency (HHV)	27-41% [98]	Available sizes	1 KW to over 18 MW [59,96]
Overall CHP efficiency	86.7-94.9 [99,100]	Fuel pressure (psig)	1-75 [98]
Effective electrical efficiency	75-80% [98]	Fuels	NG, LPG, biogas, industrial waste gas, sour gas, and manufactured gas [98]
Power-to-heat ratio	0.5 – 1.2 [98]	Uses of thermal output	Central heating, cooling, hot water, & low pressure steam [98]
Installation cost ($/KW)	900 – 1500 [101]	Power density (KW/m^2)	35-50 [98]
Maintenance cost ($/KWh)	0.005-0.015 [101]	Life cycle (year)	15-25 [101]
Availability	96-98% [98]	Noise	High [101]
Hours to overhauls	30000-60000 [98]	Part load performance	Good and Fair [101]
Start-up time	10 sec [98]	Payback period	< 7 years [59]
NO_x (kg/MWhe)	0.99 [102]	CO_2 (lb/MWhe)	650 [101]
Availability	96-98 [98]	Size (m^3)	0.77 [98]

Over the last three decades, ICE technology has undergone substantial advancements, driven primarily by the demand for higher power density (increased output per engine size), improved fuel efficiency, and decreased emissions, due to economic and environmental concerns [96].

5) Current state of the art

ICE has a long history of use, spanning more than a century. This technology has undergone extensive development and has found applications across a wide spectrum, from large vehicles to smaller devices like lawnmowers. Consequently, it is a clear choice for the prime mover in micro-CHP systems. In the past, small engines were more expensive per kilowatt and emitted more pollutants. However, significant advancements have been made to address these concerns. Techniques such as three-way catalyst, lean-burning mode, & oxidation catalyst have been implemented, resulting in NOx levels below 50 ppm and in some cases as low as 20 ppm. Typically, small engines like those found in lawnmowers are known for being loud. However, when it comes to micro-CHP prime movers designed for indoor use, endeavours have been undertaken to minimise noise levels to meet acceptable standards. The reduction of noise levels has proven highly effective for micro-CHP units. As an illustration, the ECOWILL 1-kW gas engine produces a noise level of 44 dBA at a distance of 1 meter, while a 5-kW micro-CHP unit typically emits around 50 dBA at the same distance. Micro-CHP systems, specifically those with ICE, require regular upkeep, such as changing the oil, replacing filters, and servicing spark plugs. Typically, these engines need servicing every 3000 hours. Nevertheless, the ECOWILL 1-kW micro-CHP equipped with an ICE necessitates maintenance only once every 6000 hours. This means, the system only needs to be serviced once a year, which is similar to the maintenance schedules for household hot water or heating furnaces. Diesel engines generally possess a higher compression ratio, resulting in greater efficiency compared to gasoline or NG engines. Gasoline engines use spark ignition for combustion, whereas diesel engines rely on compression to ignite the fuel. In general, gasoline engines tend to be lighter & produce less noise [60].

6) List of commercially available

Table 2-2 outlines key features of commercially available ICEs, including brand, model, fuel type, efficiencies (electrical, thermal, overall), noise levels, and dimensions.

Table 2-2: Commercially available internal combustion engines and their specifications [99][100][103][104][105][106]

Brand	Model	Fuel	Electrical Output (kW)	Thermal output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Noise (dB)	Dimensions (mm) (WxDxH)
Dachs [103]	G 5.5	Natural gas	5.5	14.8	25.6 / 28.4	93.9/104.2	48	720x1070 x1270
Dachs [103]	F 5.5	LPG	5.5	13.8	26.8 / 29.1	93.8 / 101.9	47	720x1070 x1270
Bosch [100]	CHP CE 12 NA	Natural gas	6-12	13.75-27.5	30.2	-	56	882x1600 x1263
Bosch [100]	CHP CE 19 NA	Natural gas	9.5-19	18-36	34	-	56	900x1800 x1010
Bosch [100]	CHP CE 50 NA	Natural gas	25-50	40-80	33.8	87.9	65	960x2930 x1730
Bosch [100]	CHP CE 70 NA	Natural gas	35-70	54.5-109	34.3	87.7	68	960x3275 x1730
EC POWER [99]	XRGI 6	Gas (all qualities), propane, butane	6	12.4	30.1	92.4	49	640x930x 960
EC POWER [99]	XRGI 9	Gas (all qualities), propane, butane	9	20.1	29.3	94.9	49	640x930x 960
EC POWER [99]	XRGI 15	Gas (all qualities), propane, butane	14.5	36.7	29.3	-	53	750x1120 x1170
EC POWER [99]	XRGI 20	Gas (all qualities), propane, butane	20	44.7	32.7	-	49	750x1120 x1170
EC POWER [99]	XRGI 25	Gas (all qualities), propane, butane	24	48	31	93	-	750x1120 x1170
SokraTherm [104]	FG 34	Sewage gas/Biogas	35	65	31.3	89.3	62	900x2200 x1830
EAW [105]	BHKWTypEWK10S	Gasoline	10	19	30.4	87.2	-	770x1600 x2000
Viallant [106]	Ecopower1.0	Natural gas	1	2.5	26.3	92	-	-

7) Fuel flexibility

Besides running on NG, spark ignition engines can also operate on various other types of gaseous fuels, including:

- **LPG** refers to a combination of propane and butane.
- **Sour gas** refers to NG that is in its raw, untreated form as it is drawn straight from the gas well.
- **Biogas** refers to the flammable gases generated through the natural breakdown of organic waste materials.
- **Industrial waste gases**, such as process off-gases & flare gases, originate from refineries, steel mills, and chemical plants.
- **Manufactured gases** refer to gases that are produced through gasification or pyrolysis processes, usually with low or medium Btu levels [96].

8) Benefits and limitations

Micro-CHP systems utilising internal combustion engines (ICE) offer numerous benefits. Firstly, ICE technology is well-established and widely understood. These engines can be adapted to run on various fuels such as gasoline, diesel, natural gas (NG), and landfill gas. While larger ICE can function for over two decades, smaller units tend to have a slightly shorter lifespan. ICE exhibit higher efficiency levels compared to steam engines and modern Stirling engines. Moreover, they have a faster start up time than external combustion engines [60].

However, ICE requires regular maintenance. The current maintenance costs for ICE or gas engines range from approximately \$0.005 to \$0.015 per kilowatt-hour (kWh), whereas diesel engines have a maintenance cost of about \$0.005 to \$0.01 per kWh [101,107]. Additionally, ICE present challenges related to noise and emissions [60].

A summary of the benefits and drawbacks of ICE is presented in Table 2-3.

Table 2-3: Advantages and disadvantages of internal combustion engines [98]

Advantages	Disadvantages
Quick startup capability.	High maintenance costs.
High power efficiency with flexible part-load operation.	Suitable only for low-temperature cogeneration.
Relatively low investment cost.	Higher air emissions.
Excellent load-following performance.	Generates significant low-frequency noise.
Can be serviced on-site by regular operators.	Requires cooling even when recovered heat is not utilized.
Operates on low-pressure gas.	Has many moving parts and may require significant foundation support.

9) Market analysis / Market size

Several companies have been working on or promoting micro-CHP systems that use ICE. For instance, SenerTec has successfully sold over 8,000 units in Europe, each with a 5.5 kW gas engine, for 14990 USD. Eco Power has introduced a 4.7 kW gas engine micro-CHP, adjustable to as low as 2 kW, priced at approximately 14950 USD. VectorCogen has created 15 kW systems, at an approximate price of 30000 USD. On the other hand, Honda/Osaka Gas offers a much smaller unit, offering 1 kWe for $6,800. General individual ICE are significantly less expensive. For instance, while a 1 kW gasoline engine generator could be purchased for as little as 400 USD at retail outlets like Lowe's, micro-CHP systems require additional components such as noise reduction devices, emission control, power conditioning equipment, & waste heat recovery systems. As a result, ICE-based micro-CHP systems are much more costly. Despite the market's growth and competition from various manufacturers, it is unlikely that substantial cost reductions will occur with increased sales volume, which sets it apart from technologies like Stirling engines or fuel cells [60].

10) Future industry and technology trends

Despite some advancement in enhancing ICE technology, there is still a need for further improvements in reducing noise, extending service intervals, and controlling emissions of NOx and CO to make them more suitable for micro-CHP. The goal for the Advanced NG ICE is to achieve a NOx target of 0.1 grams per horsepower hour. Additionally, to augment the fuel versatility of engines, there is a plan to make NG-fired engines adaptable for future use with dual-fuel capabilities [60,107].

11) Future developments

Over the past two decades, notable advancements have been made in ICE, leading to enhanced efficiency and decreased emissions. The implementation of electronic engine control alongside optimised combustion chamber design, such as the incorporation of pre-combustion chambers, enables engines to function efficiently on leaner fuel blends. Additionally, advancements in design & materials technology have facilitated engines to achieve greater speeds and power densities, all while simultaneously extending their lifespan. The advancements mentioned result from joint research endeavours involving private companies, research centres, universities, and the federal government [96].

2.2.2 Stirling engine

SE is a form of external combustion engine that operate using a sealed compartment containing a working fluid, commonly helium or hydrogen. These engines follow the Stirling cycle, characterised by two isothermal processes & two isochoric processes [60]. Stirling engines exhibit superior heat sink temperature capabilities and maintain efficient operation under part-load conditions, positioning them as a promising option for prime movers in micro-CHP systems [108,109]. As an emerging technology, Stirling engines are particularly well-suited for single-family homes and small multi-family residences. They provide the core benefits of micro-CHP systems, while also leveraging the advantages of SE technology featuring reduced emissions, the ability to operate on various fuel types, and minimal environmental and acoustic impact [110]. Figure 2-12 illustrates a SE-based micro-CHP unit.

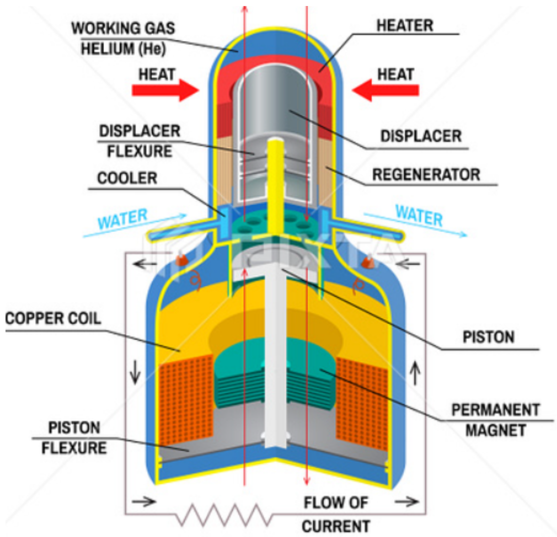

Figure 2-12: Stirling engine in a micro-CHP system [9]

Although the SE operated on external combustion, it differed significantly from other engines. The SE is a closed-cycle heat engine, effectively transforming heat energy into mechanical work. It takes in heat from an external reservoir, utilises a portion of it for mechanical work, and releases the excess heat to a heat sink. Another notable distinction is that the SE is its operation on a closed-loop cycle, wherein the working fluid remains sealed inside the system and is repeatedly recycled to facilitate heat transfer during each cycle. Additionally, the SE is regenerative, allowing it to store and recover heat during distinct phases of the cycle utilising a heat exchanger. The feature of this reduces energy loss and enhances the overall efficiency of the engine [111–113].

Both the SE and the Carnot engine have the same theoretical efficiency, representing the maximum efficiency achievable for any heat engine [60]. SE are typically compact, with sizes ranging from 1 to 25 kW, although there are a few that can reach up to 500 kW [60,114].

1) Brief history of a Stirling engine

a) Reverend Robert Stirling and his engine

The SE, derived in 1816 by Reverend Robert Stirling, a clergyman of the Church of Scotland, was a collaborative effort between Robert Stirling & his brother James, a prominent engineer at the time. They dedicated several years to developing regenerative systems [115,116]. The Stirling brothers produced several engines, some of which were utilised in practical situations. During that time, similar machines were referred to as air engines, hot-air engines, or caloric engines, with the inventor's name preceding the term [117].

The term 'Stirling Engines' was created to encompass all kinds of closed-cycle regenerative gas engines, irrespective of the specific working fluid used. Similarly, in the 19th century, the term 'Ericsson Engines' [118] was employed to encompass various kinds of open-cycle valve regenerative gas engines. During this time, substantial numbers of hot air engines were produced and utilised. These early air engines found application in various areas, primarily for power generation and water pumping [119]. Finkelstein [120] and Sier [121] have thoroughly examined the origins of these early air engines, and by Sier.

Around 1900, SE experienced significant commercial success. However, their further development was hindered due to the unavailability of appropriate materials. Eventually, the advancements in ICE and electrical machines caused the decline of SE [115].

b) Philips Stirling engine development

The Philips Electric Company in Eindhoven, Netherlands, wanted to create kerosene-powered electric power generators as a replacement for the large lead-acid batteries commonly utilised in valve radios during that era. These radios required a lot of power, and the batteries were bulky. In the late 1930s, Philips began working on Stirling machines, which sparked the current interest in this technology. They developed an SE that was significantly more efficient, faster, and had higher power density than previous models. Advancements in the design of thermionic valves & the emergence of electronic transistors, coupled with the subsequent emergence of transistor radios driven by dry batteries, rendered the intended market for the engine obsolete. Hargreaves' book provides extensive coverage of the history & technology of Philips' Stirling developments [122].

Philips understood the significance of their efforts and proceeded to develop a larger SE. They opted for lighter working fluids such as H_2 & helium to achieve higher speeds & power densities. As a result, the term "air engine" fell out of use. By 1948, Philips was testing trials on a V4 engine, with prominent car manufacturers, such as Henry Ford II, visiting their labs. Due to its silent performance and advantageous torque properties, the Stirling engine was found to be particularly suitable for ship and submarine propulsion, which Philips decided to focus on. General Motors in Detroit, Michigan, obtained a license for the SE from Philips and continued its development from 1958 to 1970. Throughout this period, they engineered a diverse array of engines spanning from 10 horsepower to 800 horsepower. Subsequently, Ford Motor Company acquired the GM license in collaboration with Philips, focusing primarily on crafting a 135kW engine tailored for the Ford Torino sedan. The Torino engine, originally developed as a torpedo motor in the GM program, was further refined at the Philips laboratories. Meanwhile, Ford dedicated its efforts to aspects such as vehicle installation, drivetrain refinement, and other related components [123].

In 1978, a collaborative effort between the US Department of Energy, Philips, and Ford commenced with the ambitious goal of developing a 67kW engine. This project received a substantial funding total of 160m USD. However, this project was terminated in the initial 1980s when Philips management made the difficult decision that power system development did not align with their corporate strategy. As a result, the research and development unit at Philips was disbanded. Dr. Rolf Meijer, who had been leading the Philips Stirling research team, happened to be in the US during this period, aiding Ford in their SE development efforts. Instead of an option for an early retirement back home, he decided to stay in the US and establish Stirling Thermal Motors. This endeavour later evolved into STM Power Inc. in 1990. STM Power Inc. focused on developing onsite electricity and cogeneration systems, also known as "Power Units." STM Power Inc. believed that the electricity and heat generated by their Power Units would offer superior cost-effectiveness in the distribution energy market, outperforming alternative energy conversion technologies such as micro turbines, fuel cells, and photovoltaic systems. In December 1999, STM Power Inc. began testing a 25 kW Power Unit and installed their Sun Dish Solar system, a renewable distributed generation product, in five test facilities. Additionally, they developed a 10 kW Power Unit leveraging the STM 4-70 Stirling engine as its foundation. This engine was originally constructed through collaboration with General Motors Corporation, aimed at integration into GM's hybrid electric vehicle. The 10 kW Power Unit, when configured as a Power Unit, was specifically engineered to produce 10 kW of electricity alongside 20 kW of heat output. It had a compact size, measuring approximately 3ft * 3ft * 2ft, similar to a small residential air conditioning (AC) unit [117,119].

2) Stirling engine types

There are three main types of SE. The Alpha-type engine achieves its operation by connecting the power pistons across multiple cylinders to transfer the working gas while maintaining different temperatures in the cylinders. On the other hand, both Beta and Gamma types of SE utilise a displacer piston to oscillate the working gas back and forth between the hot and cold heat exchangers positioned within a shared cylinder, facilitating the thermodynamic cycle [124,125]. Figure 2-13 shows the Alpha, Beta & Gamma SE.

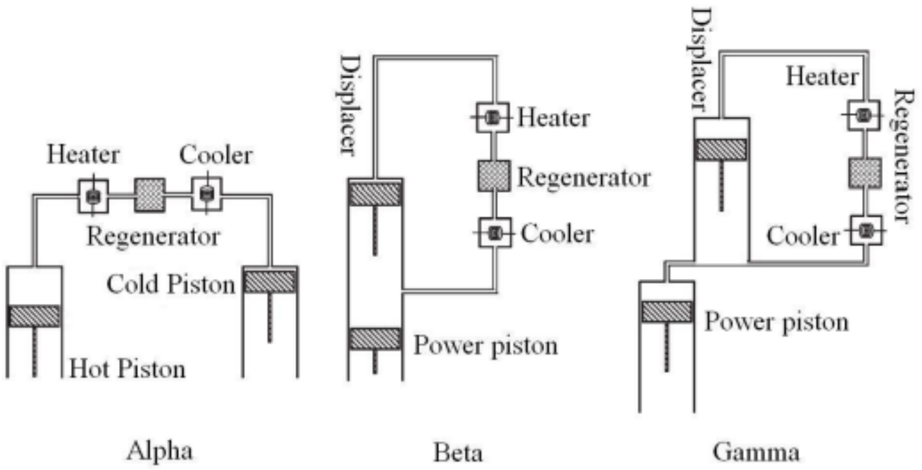

Figure 2-13: Stirling engine types (Alpha, Beta, and Gamma) [126]

a) Alpha Stirling

A SE configured in an alpha arrangement comprises two distinct power pistons located in individual cylinders. These cylinders are classified as the "hot" piston cylinder and the "cold" piston cylinder. The hot piston cylinder is integrated within the higher-temperature heat exchanger, while the cold piston cylinder is positioned within the lower-temperature heat exchanger. Despite the engine’s high power-to-volume ratio, it faces technical issues arising from typically elevated piston temperatures and the challenges in maintaining the durability of its seals [125].

b) Beta Stirling

In a beta configuration SE, both a power piston and a displacer piston inhabit a unified cylinder and are connected to a common shaft. The displacer piston, engineered with a loose fit, operates without extracting energy from the expanding gas. Its main purpose is to transfer the working gas from the heated heat exchanger to the cooled counterpart. As the working gas moves towards the warmer end of the cylinder, it undergoes expansion, exerting force onto the power piston. Conversely, when the gas is directed toward the colder end of the cylinder, it shrinks in size. The kinetic energy of the system, often aided by a flywheel, subsequently drives the power piston in the reverse direction, leading to gas compression. In contrast to the alpha configuration, the beta variant overcomes the technical challenges associated with seals that move while hot [124,125].

c) Gamma Stirling

A gamma SE closely resembles a beta configuration, featuring a separate cylinder for the power piston. Both cylinders, housing the power piston displacer piston respectively, are linked to a shared flywheel. The gas within these cylinders can freely move between them, maintaining unity as a singular entity. This setup yields a reduced compression ratio, offers simplified construction and is often utilised in SE featuring multiple cylinders [124,125].

3) Stirling engine components

The main components of a Stirling engine include:

- **Cylinders:** Enclosed spaces housing the working gas, with separate sections for hot and cold regions.
- **Pistons:** Typically comprising a power piston that drives the crankshaft and a displacer piston that moves the gas between hot and cold sections.
- **Cooler:** A heat exchanger that removes heat from the working gas, facilitating efficient compression.
- **Heater:** A heat exchanger that supplies thermal energy to the working gas, causing it to expand.
- **Crankshaft:** Converts the linear motion of the pistons into rotational power.
- **Gearbox:** Adjusts the rotational speed of the crankshaft to match the desired output power.
- **Generator:** Converts mechanical energy from the rotating crankshaft into electrical power [127]

4) Fundamentals of Stirling engines

The following are the key fundamentals of a SE, including the heat engine principles, thermodynamics cycle, ideal versus conventional SE, and various control mechanisms, including temperature, pressure, stroke length, phase, dead space, and speed control.

a) Heat engine principles

Heat engines operate through cyclic processes, where a gas absorbs heat at high temperatures, releases heat at lower temperatures, and generates work in the process. In the 1820s, Carnot [128] demonstrated that the maximum possible efficiency of a reversible heat engine is solely determined by the temperature difference within the cycle [129].

$$\eta_{carnot} = 1 - \frac{T_C}{T_H} \qquad \text{Equation 2-22}$$

Where η represents efficiency, T_H (K) represents the temperature of the heat source, and T_C (K) represents the temperature of the heat sink. The processes occurring in even the most basic physically realised thermal machine are complex, making it impossible to determine precisely what happens at each moment. Instead, a theoretical model is adopted, where various events are idealised to the extent required for approximate analysis. To simplify the study of its operation, a recurring sequence of thermodynamic processes, known as a cycle, is assumed [117].

b) Thermodynamics Cycle

A thermodynamic cycle is composed of a sequence of processes during which heat and work are transferred, and system properties such as pressure, temperature, and volume change, ultimately returning the system to its initial state [130]. During this cycle, the system is capable of delivering work to its surroundings, functioning as a heat engine [117].

The state variables are defined by the thermodynamic condition, and their total change over a full cycle is zero. On the other hand, process variables like heat and work are path taken and accumulate to non-zero values. According to the First Law of Thermodynamics, the total heat supplied to the system equals the work it produces over one cycle. This cyclic process is what enables continuous operation, making thermodynamic cycles essential to energy systems. In real-world applications, these cycles are often modelled as quasistatic processes [131].

Thermodynamic power cycles underpin the operation of heat engines, which generate the majority of the global electricity and power nearly all motor vehicles.

These cycles are classified based on the heat engines they model. The Otto cycle [132] is used for gasoline engines, while the Diesel cycle [133] represents diesel engines, both of which are ICE. The Brayton cycle [134] represents gas turbines and jet engines, whereas the Rankine cycle [135] describes steam turbines, both of which represent external combustion engines.

Thermodynamic cycles fall into two main categories: power cycles and heat pump cycles [136]. Power cycles transform heat into mechanical work, whereas heat pump cycles use mechanical work to move heat from a lower temperature to a higher one. If a cycle consists solely of quasistatic processes, these cycles can function as either a power cycle or a heat pump cycle, depending on the direction of the processes. On a pressure-volume (PV) diagram [130], clockwise cycles represent power cycles, while counter clockwise cycles correspond to heat pump cycles.

The PV diagram provides a graphical representation of work done in a thermodynamic cycle, plotting pressure versus volume. This visualisation fully characterises a simple thermodynamic system and allows for quick calculation of the net work done, which corresponds to the enclosed area within the cycle on the diagram. In an ideal system, state properties return to their initial values at the end of the cycle, forming a closed loop on the PV diagram. As depicted in Figure 2-14, the diagram's Y-axis represents pressure 'P' (Pa), while the X-axis represents volume 'V' (m^3) [117].

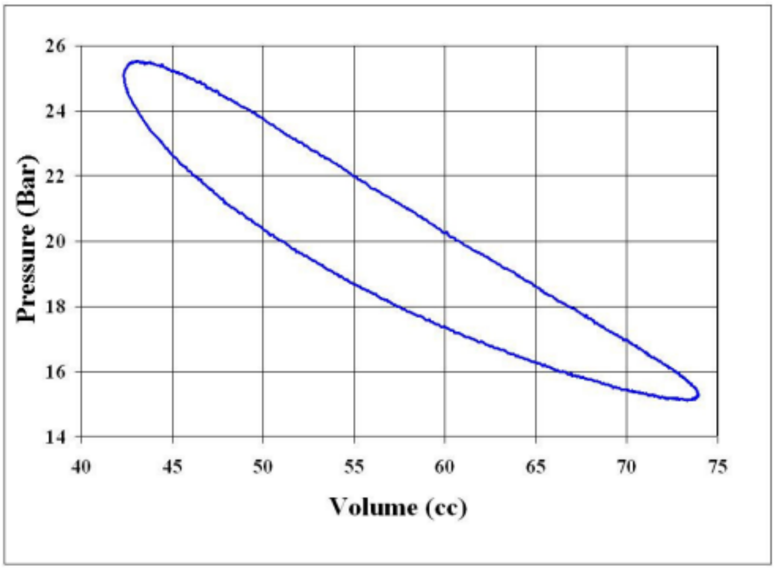

Figure 2-14: P-V graph of a Stirling engine [117]

The network, denoted as 'W' (J), performed by the cycle is defined by the area enclosed within the loop as shown in Equation 2-23.

$$W = \oint \boldsymbol{PdV}$$ Equation 2-23

Here W (J) denotes the total work, P (Pa) represents the pressure, and V (m^3) signifies the volume. This total work is equivalent to the net heat, Q (J), transferred into the system.

$$W = Q = Q_{in} - Q_{out}$$ Equation 2-24

Equation (2-24) illustrates the energy balance between in a thermodynamic cycle and is often likened to an isothermal process with infinite heat exchange. While internal energy may fluctuate during different stages of the cycle, the system's energy returns to its initial state by the cycle's end. When the process follows a clockwise direction, the work (W) is positive, indicating it is functioning as a heat engine. If the cycle moves counter clockwise, the work becomes negative, representing a heat pump [117].

A Stirling machine operates on a closed regenerative thermodynamic cycle [136], where the working fluid undergoes periodic compression and expansion at varying temperatures. The flow is regulated by changes in volume, enabling the conversion of thermal energy into mechanical work, or vice versa. Stirling engines can serve as prime movers, heat pumps, refrigeration engines, or pressure wave generators.

c) *Ideal and conventional Stirling engines*

In the preceding discourse, adopted the assumption was adopted that all processes adhered to reversibility in terms of thermodynamics. Additionally, assumed the compression and expansion phases to be isothermal, indicating instantaneous heat exchange between the cylinder walls and the working fluid. Additionally, it was presupposed that every component of the working fluid participated in either the expansion or compression phase, disregarding any vacancies within the regenerator matrix, clearance spaces, or cavities that could contribute to the dead volume. It was posited that the regeneration process operated flawlessly, characterised by an infinite heat transfer rate between the regenerator matrix and the working fluid, thereby ensuring perfect thermal exchange with no losses. The movement of the piston and displacer was presumed to be intermittent to facilitate the distribution of the working fluid. Any effects of fluid dynamics, mechanical friction, & leakage were ignored. In real-world engines, these elements typically lead to a thermal efficiency lower than the Carnot value of the theoretical Stirling cycle. The practical thermal efficiency is often expressed as a portion of the ideal Carnot efficiency. A measurement greater than 0.3 indicates a well-engineered Stirling engine [117,123].

In practice, it is difficult to achieve the perfect piston and displacer motions proves challenging due to the utilisation of real-world devices, such as springs, linkages, & flywheels, which feature continuous velocity profiles. These components are commonly employed for storing, regulating, and transmitting energy. Although mechanisms could be designed to exhibit stepped velocity profiles through the use of cams, their physical implementation is constrained by inertial forces and elasticity. In traditional engines, the piston and displacer typically move in a sinusoidal manner. Figure 2-15 illustrates the movement profiles of the piston & displacer in a conventional SE. When this engine is running, it deviates from the ideal scenario due to the almost sinusoidal movement of the pistons. Consequently, the compression and expansion phases do not occur entirely within either of the two compartments [117].

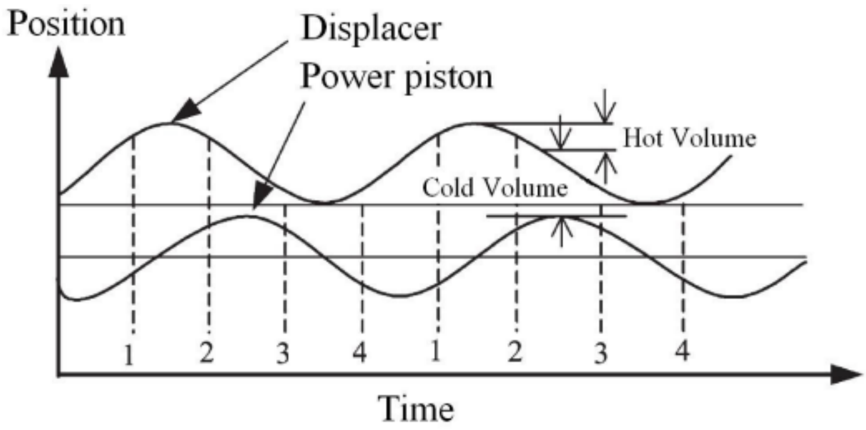

Figure 2-15: The conventional Stirling engine motion profile [126]

The pressure-volume diagram of an engine featuring a sinusoidal piston and displacer movement resembles that of a kinematic SE. The engine's work is delineated by the region encompassed within the PV diagram. At moderate speeds ranging from 500 to 1500 Revolutions per minute (RPM), it is probable that the compression and expansion processes become adiabatic conditions (without a heat exchanger) rather than remaining isothermal conditions. Dedicated heat exchangers are necessary at both the hot and cold ends to enhance heat transfer. However, the introduction of these heat exchangers leads to higher flow losses and dead volume, thereby ultimately impacting the total efficiency of the system [117].

d) Stirling engine control

The efficiency of a SE is determined by several elements including the temperatures at the hot & cold extremities, the ratio of the swept volume to the overall unwept working gas volume, the phase angle difference between volume fluctuations in expansion & compression spaces, the average pressure of the working fluid during the cycle, the operational velocity of the engine, and the attributes of the load connected with the engine. In theory, each of these variables could be utilised to manage & fine-tune the engine's power output or operational velocity [117].

e) Temperature control of Stirling engines

Traditional micro-CHP setups rely on regulating the heater head's temperature. The control mechanism manages the fuel supply to the burner system, adjusting it as needed to regulate the temperature of the hot end and efficiently generate power at a consistent rate. However, owing to the system's substantial thermal inertia, achieving a stable state can be a gradual process, often taking several minutes [117].

f) Pressure control of Stirling engines

In previous iterations of automotive engineering, SE was utilised alongside pressure control. This involved having a reservoir of high-pressure gas, which could be introduced into the engine's operational area via a control valve. Initially, when the cold fluid is introduced, there is a transient reduction in engine performance as it needs time to attain optimal working temperature. However, once this initial phase is over, the augmented pressure results in an elevated power output. To decrease the power output, the working fluid is released from the operational region, compressed, and returned to the reservoir for storage [117].

g) Stroke control of Stirling engines

Changing the piston's length and/or altering the displacer stroke serves as a potent method for regulating the power generated by an SE. When the stroke is shortened, the volume of air moved by the engine decreases, resulting in a lower pressure ratio (PR) and reduced power output. This decline in power can be attributed to the diminished pressure ratio & volume. However, this also leads to an increase in the volume of unused fluid, termed dead volume, ultimately compromising the engine's efficiency. Engine designers always strive to minimise the dead volume to improve efficiency. In the past, some automotive engines utilised dead volume control mechanisms to facilitate rapid acceleration & deceleration [117].

h) Phase control in Stirling engines

In a SE, volume changes occur in the expansion space prior to the compression chamber, exhibiting a phase shift α. This ensures the absorption of thermal energy within the expansion area & subsequently expelled within the compression area. When there's no phase shift, the pistons move in perfect synchronously, but in opposite directions. Although the high volume and pressure ratios no beneficial work is performed. This is evident on the PV diagram by a vertical line with no enclosed area. As the phase angle ascends, power output elevates until it peaks around 90°, thereafter decreasing with continued phase angle increase. Approaching 180°, the pistons synchronise their movement, propelling the working fluid between the compression and expansion spaces. The overall capacity of the operational area remains consistent, with only a minor alteration in pressure. This occurs as the working fluid undergoes temperature variations, reaching its lowest point when the compression space volume peaks and its highest point when the expansion space volume is at its maximum. However, no mechanical work is performed due to the unaltered total volume of the working space. Once more, the PV diagram shows a vertical line devoid of any enclosed area. If the phase angle exceeds 180°, the functions of the two spaces will be reversed. The space that previously absorbed heat will now compress, and vice versa. A negative power output indicates the necessity of inputting power to sustain operation. With ample input power, the engine will persist in operating forward, functioning as either a heat pump or refrigerator. At lower temperatures, it will efficiently absorb heat, and conversely, at high temperatures, it will promptly release heat. The phase control mechanism operates immediately. While traditional engines have overlooked this control method, the Active SE aims to delve into this precise control mechanism for kinematic SE [117].

i) Dead volume control

Modifying the empty areas within the total operational volume of the workforce is achievable by interlinking reservoirs of different capacities within the crankcase of the engine. Utilising valves for the purpose of selectively including or excluding particular dead volumes as a control method, although this approach is not efficient or simple to execute [117].

j) Speed control

The operating speed of a SE is determined by the applied load. In stationary applications, standalone systems are typically governed to maintain a consistent speed, regardless of the frequency. However, direct-drive automotive systems are designed to function at various speeds and power levels. The speed of a SE directly affects its power output, and the power can be adjusted by controlling the speed.

This is especially important in Stirling refrigerators, specifically in small cry coolers used for infrared night vision devices. When starting up, cry coolers are operated at maximum speed to quickly reach the desired low temperature. Once the cold tip reaches the desired temperature, a feedback control mechanism is employed to reduce the system's speed and maintain the temperature [117].

5) Application and the characteristics

This section presents a detailed overview of the applications and characteristics of Stirling engines.

a) Applications:

There are numerous uses for SE [137].

- *Cogeneration (CHP)*

A SE within a cogeneration unit can utilise waste heat generated by the principle of the 2nd law of thermodynamics, enabling its utilisation for various industrial or agricultural purposes [138].

- *Solar power generation*

SEs, when positioned at the focal point of a parabolic mirror have the ability to convert solar energy into electricity more efficiently than certain photovoltaic cells [116,138].

- *Submarines*

Stirling-powered submarines offer a significant advantage over conventional submarines by enabling them to remain submerged for extended periods. Swedish shipbuilder Kockums pioneered the installation of SE in submarines, eliminating the need for resurfacing to recharge batteries. This innovation has effectively increased the submarine's submersion capability from a matter of days to several weeks [139].

- *Nuclear power plants*

SEs has the potential as substitutes for steam turbines in nuclear reactors, offering the potential to amplify plant efficiency and diminish the generation of radioactive waste. Operating with liquid sodium as a coolant, these engines eliminate the requirement for water throughout the entire operational cycle [137].

- *Educational demonstration*

A SE that operates at a low-temperature difference can function with any small temperature difference, such as the disparity between the palms of a hand. This type of engine is capable of producing approximately 1 Watts of power from a person's palm. The

United States has also created a SE for the purpose of producing electricity during space exploration [138].

b) Characteristics

Solar dish systems have the capability to utilise Stirling or Brayton cycle engines. Stirling cycle engines integrated into solar dish systems are externally heated engines, operating at high temperatures and pressures using a working gas. In advanced SE, the working gas temperature can exceed 700°C, while the pressure can reach up to 20 MPa. The Stirling cycle involves heating and cooling the working gas through consistent-temperature & consistent-volume processes. SE typically incorporate a regenerator, which captures heat during the cooling phase and releases it during heating. Specialised pistons and cylinders are employed to achieve these processes, with some engines employing a displacer to transfer gas between hot and cold regions. Typically, power is extracted through a rotating crankshaft, except in the case of a free-piston configuration, where the pistons move freely and power is extracted through a linear alternator or pump [140]. Table 2-4 displays the key attributes of the Stirling engines.

Table 2-4: Characteristics of the Stirling engines

Characteristic	Stirling engine	Characteristic	Stirling engine
Electric efficiency (HHV)	15-35 [101]	Available sizes	1 KW -150KW [141]
Overall CHP efficiency	90-96 [142,143]	Life in year	15 years [12]
Thermal efficiency	70–85 [101]	Fuels	Any fuel [144]
Power to heat ratio	0.1-0.4 [98]	Fixed OEM (k€/MW)	3.333 [12]
CHP Installed cost ($/KWe)	3700 (£2937) [145]	Part Load	Good [144]
Start-up Time	20 min – 1 hr. [146]	Temperature of the heat source (°C)	650-1100 [101]
Temperature of the cooling medium (°C)	20–80 [101]	Noise	Low [144]
Availability	99% [98]	NO_x (kg/MWhe)	0.63 [102]
Size (m^3)	0.19 [98]	CO_2 (lb/MWhe)	999.72 [98]

6) Current state of the art

The latest developments in SE-based micro-CHP systems showcase significant advancements in efficiency, fuel flexibility, and integration with renewable energy sources. Modern Stirling engines are now attain electrical efficiencies of approximately 30%, with overall system efficiencies exceeding 90% by utilising advanced heat exchangers and regenerative techniques. These systems exhibit fuel flexibility, operating effectively on natural gas, biogas, and hydrogen, enhancing their adaptability for low-carbon energy solutions. Additionally, integrating Stirling engines with renewable energy sources, such as solar thermal energy, further increases their efficiency and sustainability. The market for SE-based micro-CHP systems is projected to grow substantially, driven by rising interest in decentralised energy generation and supportive policies. Challenges remain, including initial costs and operational reliability, but on-going research aims to address these issues and optimise performance [147,148].

7) List of commercially available

Table 2-5 presents a wide-ranging analysis of commercially available SEs.

Table 2-5: Commercially available Stirling engines and their specifications [142][143][149][150][151]

Brand	Model	Electrical Output (kW)	Thermal output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Noise (dB)	Dimensions (mm) (WxDxH)
Viessmman [142]	Vitotwin 350F	1	3.6-26	15	96	-	-
Baxi [149]	Baxi ECOGEN	1	7.7	-	90	-	450x426x950
Simons [150]	QCHP-3500	3.5	14	20	103% LHV (Lower heating value); 91% HHV	50	-
Simons [150]	QB-7500	7.5	30	20	103% LHV; 91% HHV	50	-
Inspirit [143]	Inspirit m-CHP	6.4	15	15	90	-	630x650x850
Okofen [151]	ÖkoFEN Smart_e	0.6	9	-	90	-	1175x1150x1958

8) Fuel flexibility

While air is commonly employed as the primary working fluid in SE, H_2, and helium are also utilised to enhance performance because of their superior thermal properties [152]. The study concludes that the engine's performance is influenced by the type of working fluid used. The SE performed the best when H_2 was used as the working fluid. However, the widespread use of H_2 in SE is limited due to its elevated risk of flammability. Additionally, the study revealed that the engine exhibited improved performance at elevated pressures. Moreover, the engine's speed significantly influenced its performance, with peak results observed at 1300 rpm when operating with H_2 under the maximum standard gas pressure. After H_2, helium was found to be the second-best choice for a working fluid, especially considering the flammability concerns associated with H_2 [153].

9) Benefits and limitations

The SE is versatile in its fuel options and capable of utilising a diverse array of energy sources, including NG, solar energy, and gasoline due to its external combustion system. The combustion process can be easily regulated, resulting in potentially low emissions. Compared to ICE, the SE produces less noise. Additionally, it requires minimal maintenance and typically has a long lifespan [60,107,116]. One major benefit of the SE in a micro-CHP system is that any excess heat from the burner could be easily employed for space heating and hot water purposes [60].

Listed below are some of the primary drawbacks of SE [60,107,116,154]:

- The SE is currently priced at approximately $2,000 per kilowatt, which is quite expensive.
- The engine requires several minutes to reach optimal temperature prior to power generation, and it is unable to rapidly adjust its power output.
- As previously stated, there remain concerns regarding the longevity of specific components.

The benefits and drawbacks of Stirling engines are outlined in Table 2-6.

Table 2-6: Advantages and disadvantages of Stirling engines [98]

Advantages	Disadvantages
Reduces component wear and minimizes vibration levels.	High operational costs of the engine.
Fewer moving parts, greater fuel flexibility.	Concerns about long-term reliability.
Continuous fuel combustion results in lower noise compared to pulsed combustion.	Heat transfer characteristics reduce the engine's responsiveness.
Reduced NOx and unburned fuel emissions.	Low specific power and electrical efficiency.

10) Comparison of gasoline engines and Stirling engines

An SE, or Stirling engine, belongs to a class of heat engines designed to transform thermal energy into mechanical motion. It constitutes one segment of a broader category of heat engines that includes the ICE found in cars. While the ICE uses fuel combustion within a confined space, the SE relies on an external heat source to heat the working substance [155].

11) Market analysis / Market size

There are over 20 manufacturers of SE globally [107]. At present, SE has found applications in different sectors such as residential, space, and marine industries, and even in vehicles like the Segway scooter [156].

As of now, the overall market for SE is relatively limited. The primary purpose of a stand-alone SE is to generate power through waste heat recovery. WhisperTech, based in the UK, has been developing and implementing SE-based micro-CHP systems, boasting a capacity of 1 kW. Should these micro-CHP applications demonstrate success, there may be a higher demand for SE-based systems in the housing industry. This could lead to advancements in SE technology and a decrease in cost [60].

12) Future industry and technology trends

The current SE technology has two significant drawbacks: a lack of durability and high cost [107]. The challenges related to durability in SE involve various issues such as leakage in shaft seals, piston ring integrity, and bearing performance. These challenges include minimising stress & corrosion in high-temperature areas and addressing abrasive particle production by piston rings. Despite these hurdles, SEs are designed for extended lifespans and require minimal maintenance [60,107].

13) Future developments

Future developments of SE-based micro-CHP systems are expected to focus on enhancing efficiency, fuel flexibility, integration with renewable energy, and cost-effectiveness. These advancements will enable Stirling engines to play a critical role in decentralised, low-carbon, and sustainable energy solutions, supporting global energy transition goals [147].

2.2.3 Fuel cells (FC)

Fuel cell is an advanced technology known for its strong safety record, sustainability, and environmental advantages. In CHP systems, the heat generated typically comes as low-pressure steam or hot water, within its quality determined largely by two key factors: the type of FC employed and its operational temperature. Hydrogen, the fuel used in fuel cells, is produced from various sources, including coal, natural gas, methanol, or gas. A fuel cell operates by utilising electrochemical reactions to directly transform the chemical energy contained in the fuel into both electricity and heat, eliminating the need for combustion [98]. An FC functions as a device harnessing electrochemical reactions to efficiently convert fuel derived chemical energy into usable power and het, bypassing the necessity for combustion. Essentially, they can be seen as a fusion of a battery and a heat engine, hence earning them the occasional moniker ‘’electrochemical engines’’ [157]. Like batteries, FC is made up of individual components such as a cathode, an anode, and an electrolyte. These components are linked together to create a stack. Conductive interconnectors, also known as bipolar plates, serve a pivotal role in distributing fuel and oxidants to each cell while establishing electrical connections between them. Additionally, coolant fluid may be circulated through channels within the interconnectors or via extra plates interspersed between the cells. As a general reference, the individual cells used in micro-CHP systems are approximately 100 cm^2 in size and have a thickness of a few millimetres. These cells generate a current of 20 amps to 100 amps at a voltage of 0.7V. To increase the voltage, between 20amps and connecting 100amps of these cells in series yields a stack voltage ranging from 10V to 50V. This configuration produces approximately 1kW of direct current (DC) power [158].

There are various FC technologies available, each with unique designs that are suitable for different purposes. However, they all have common features such as being highly efficient, operating quietly, the absence of moving components, and minimal or zero emissions at the location of utilisation. Furthermore, the modular stack design allows for flexibility in capacity, unlike mechanical heat engines, which have limitations on minimum capacity. There are various categories of FC, primarily determined by the electrolyte type employed. This electrolyte dictates the chemical reaction, the catalyst, the operating temperature range, and the fuel needed for the cell [159]. Some of the most hopeful varieties include Proton exchange membrane fuel cell (PEMFC), Molten carbonate fuel cell (MCFC), Solid oxide fuel cell (SOFC), Alkaline fuel cell (AFC), and Phosphoric acid fuel cell (PAFC) [98,159].

H_2 stands out as the most desirable fuel due to its exceptional electrochemical performance and longevity. At the anode of the cell, electrons are removed from the H_2 molecules, resulting in the creation of ions. The ions proceed to traverse a conductive electrolyte until they are combined with oxygen (O_2) at the cathode. With their electrons removed, they initiate an electric current coursing through the interconnected cells and circuitry, as depicted in Figure 2-16. The specific reactions at play differ based on the specific type of FC employed, given the multiple technologies available. However, the overall balance is the opposite of electrolysis [160,161], where H_2 represents hydrogen, O_2 denotes oxygen, and H_2O stands for water.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad \text{Equation 2-25}$$

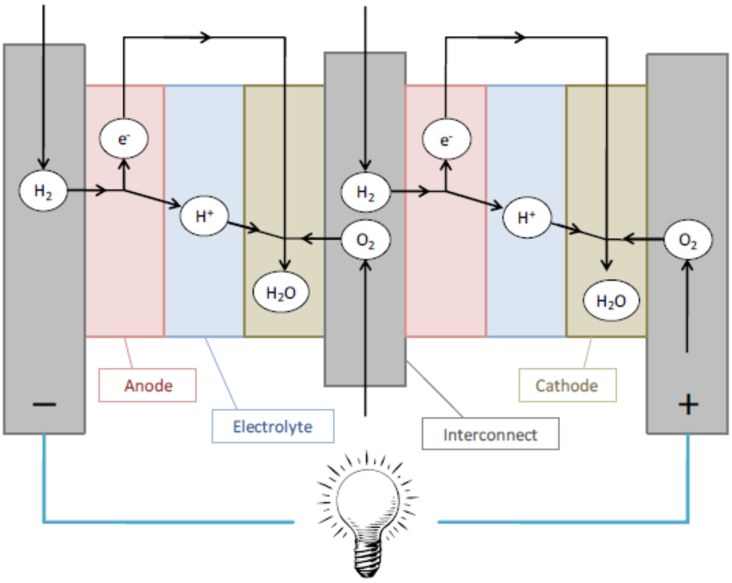

Figure 2-16: Archetypal fuel cell diagram [158]

The main benefit of an FC is its lack of toxic gas emissions, as its primary power conversion process is based on electrochemical reactions rather than combustion. While the initial cost of fuel cells remains relatively high, they continue to be in demand for CHP applications due to their low emissions, minimal noise levels, strong part-load performance, and attractive market incentives [98]. Figure 2-17 illustrates the diagram of a FC-based micro-CHP system.

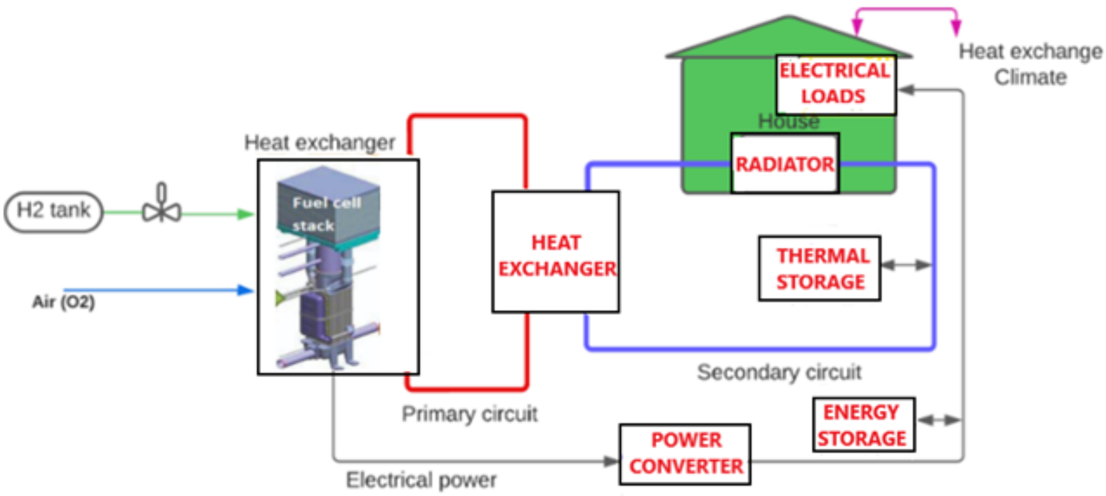

Figure 2-17: Diagram of a fuel cell-based micro-CHP system, adopted from [73]

The most commonly used fuel cell technologies for domestic applications are

SOFC (Solid Oxide Fuel Cell): It operates at high temperatures, typically between 800°C and 1,000°C, which is the highest of all fuel cell types. When converting fuel solely to electricity, its efficiency exceeds 60%. However, when the heat produced is also utilised, the overall efficiency can exceed 90% in fuel-to-energy conversion [162]. Figure 2-18 depicts a micro-CHP system featuring a flame-assisted SOFC.

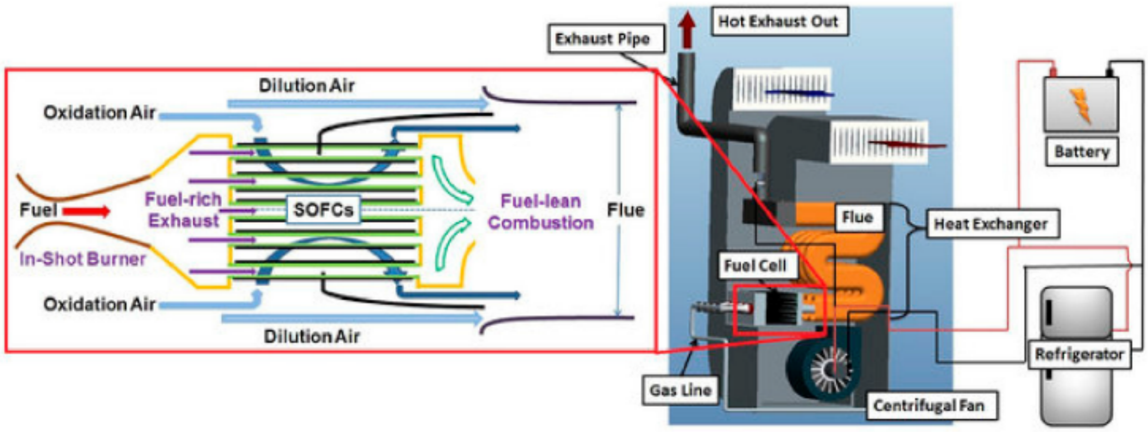

Figure 2-18: Micro-CHP system with a flame-assisted SOFC [163]

PEMFC (Proton Exchange Membrane Fuel Cell): The PEMFC utilises a water-based electrolyte system with an acidic polymer membrane and platinum electrodes. These FC generally run at lower temperatures (below 100°C) and are capable of adjusting their electrical output to respond to varying power requirements [164]. Figure 2-19 provides a schematic representation of a house powered by a PEMFC.

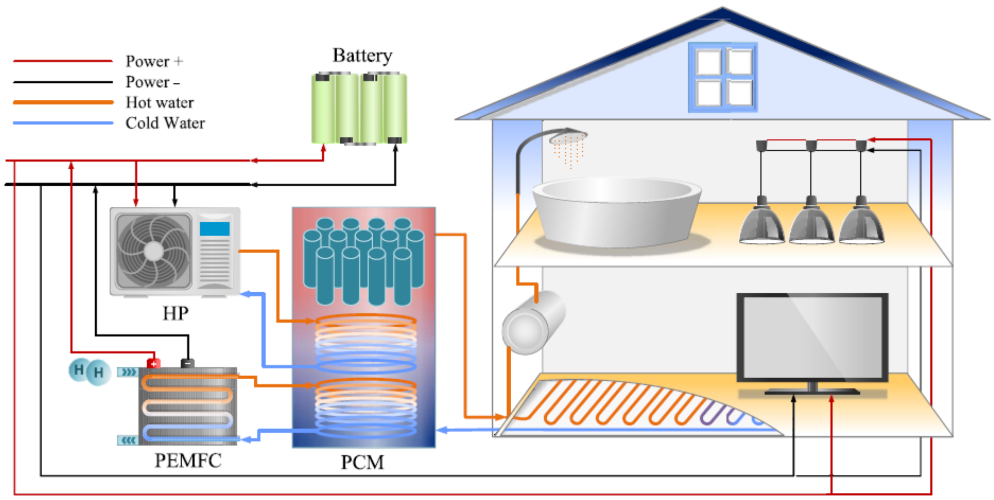

Figure 2-19: Schematic illustration of a house powered by PEMFC [165]

1) Brief history of a fuel cell

In 1839, Sir William Grove, hailed as the "Father of the fuel cell," discovered the potential of FC, and unveiled the possibility of electricity production through the reversal of water electrolysis. The moniker "FC" was officially introduced in 1889 by

Charles Langer and Ludwig Mond, as they embarked on pioneering work to construct the inaugural functional FC utilising air and coal gas. Despite subsequent efforts in the early 1900s aimed at crafting FC capable of converting coal or carbon into electricity, the rise of the ICE briefly halted further progress in this emerging technology [166].

In 1932, Francis Bacon created an FC device that was the earliest successful one. It utilised alkaline electrolytes and nickel electrodes, which were more affordable compared to those utilised by Mond and Langer. However, it took until 1959 for Bacon and his team to showcase a practical 5kW FC system due to various technical challenges. In that same year, Harry Karl Ihrig introduced his well-known tractor powered by a 20-horsepower FC. NASA started developing a small electricity generator for space missions in the late 1950s. They funded numerous research contracts related to FC technology, which eventually proved to be useful in supplying electricity during space missions. Over time, numerous manufacturers & government agencies have remained committed to advancing research in FC technology for applications such as FC vehicles and other uses. It is anticipated that FC energy will replace traditional power sources in the future, ranging from small FC for cell phones to cutting-edge FC powering vehicles in stock car racing [167–169].

2) Fuel cell micro-CHP systems

Operating an FC stack alone in a household setting would be extremely difficult, like expecting a car engine to produce hot water and usable electricity. Additional systems are necessary to create suitable operating conditions and effectively extract power and heat from the stack. In terms of both volume and cost, the FC stack typically represents a fraction smaller than one-fourth of a micro-CHP system. Figure 2-20 depicts the amount of equipment enveloping the FC stack, positioned centrally within the diagram.

- A fuel conversion system is utilised to transfer NG into an H_2 stream that meets the required purity standards.
- An inverter is employed to transfer the DC power output into Alternating current (AC) power, synchronised with the grid.
- Heat exchangers extract heat from the chimney and facilitate its transfer into the building.
- A hot water reservoir is implemented to store and retain this heat for use during periods of non-usage.

- The system includes pumps, sensors, valves, and a complex network of pipes to transport fuel, air, and coolant to the stack. Additionally, they facilitate the removal of waste gases, heat, and electricity from the system.
- A system controller (omitted from the illustration) to control the amount of fuel being supplied, the level of power being generated, and all of the associated subsystems [158,170].

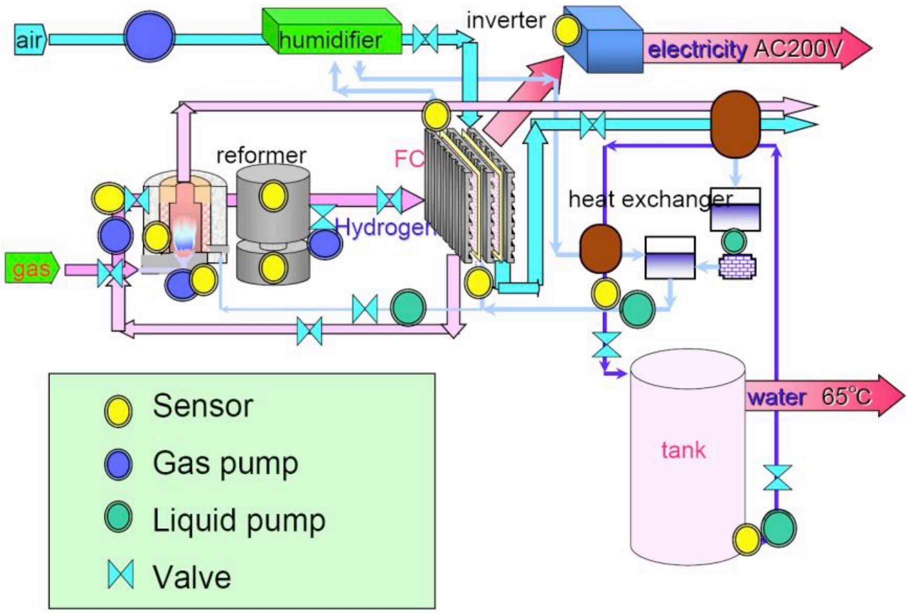

Figure 2-20: Stationary fuel cell schematic diagram based on CHP system [171]

The previous section highlighted the differences between stack technologies, and these differences profoundly affect the functionality of a micro-CHP system. An illustrative example is the necessity of precious metal catalysts to maintain efficient electrode reaction kinetics due to the low temperature of FC, thereby ensuring optimal power output. However, this escalation in material cost for the system & requires strict fuel quality tolerances. Conversely, higher temperature systems need prolonged periods for warm-up when the system starts from atmosphere temperature, rendering them unsuitable for frequent on/off cycles throughout the day, particularly when energy demand fluctuates. Additional distinctions among systems contain the requirement for electrolyte humidification in PEMFC (as depicted in Figure 2-20), the need for electrolyte storage and the circulation pumps in AFC and PAFC configurations, and the necessity of a high-temperature kiln to encapsulate the stack of SOFC. The next parts provide a summary delineating the requisites and qualities of these different sub-systems to elucidate the composition of a standard micro-CHP system based on FC [158].

3) Overview of stack technologies

While numerous FC technologies are being researched and developed, only a handful is appropriate for residential micro-CHP applications. Crucially, the FC stacks needs to be able to be produced at a low cost and have a long lifespan, even in less-than-ideal conditions with impurities in the H_2 fuel. Safety and practicality are also important factors, ruling out the use of a pressure vessel. Additionally, high operating efficiency is crucial for cost-effectiveness. Ideally, the chosen FC technology ought to be firmly established, supported by demonstrations, and research primarily focused on its use in the residential market. The study considered the following technologies, guided by these criteria:

- PEMFC
- SOFC
- PAFC
- AFC

During the past decade, there has been significant research and commercial advancement in residential CHP systems using PEMFC and SOFC stacks. Numerous major companies are actively involved in this market, with their products undergoing extensive testing through large-scale field trials conducted in South Korea, Japan, & Germany. Table 2-7 outlines an overview of the standard configuration of each FC stack, detailing their operational parameters & ability to withstand fuel impurities [157,172].

Table 2-7: The overall operating features of every fuel cell technology [158]

		PEMFC	SOFC	PAFC	AFC
	Electrodes	Pt, Ru, C, PTFE	Ni, LSM	Pt, C, PTFE	Pt or Ni, C, PTFE
	Electrolyte	Solid polymer (PFSA)	Ceramics: YSZ, LSM	Liquid H2SO4	Liquid KOH
	Interconnect	Graphite, steels	Chromium alloys, steels	Graphite	Graphite, metal or plastic
	Operating Temperature	30-100°C	500-1000°C	200-250°C Must remain >70°C	50-200°C
	Fuels	H2	H2, CO	H2	H2
Fuel Tolerance	Sulphur (as S, H2S)	< 0.1 ppm	< 1 ppm	< 50 ppm	?
	CO	< 10-100ppm	Fuel	< 0.5-1%	< 0.2%
	CO2	Diluent	Diluent	Diluent	< 100-400ppm or < 0.5-5%
	CH4	Diluent	Fuel / Diluent	Diluent	Diluent
	NH3	Poison	< 0.5%	< 4%	?

4) Fuel cell system/Components

Error! Reference source not found. illustrates an FC system tailored for micro-CHP application, showcasing the array of equipment & interconnections involved. The specific setup may differ depending on the specific FC technology employed. However, a typical FC system typically comprises several subsystems, including an FC stack, heat management, fuel supply, power conditioning, instrumentation and control, oxidant supply, water management, and potentially hybrid components [159].

a) Fuel cell stack

The heart of an FC system lies in its FC stack, which serves as a primary component. It usually consists of numerous FC. An FC on its own has an extremely low voltage, usually less than 1 V, and can only generate a small amount of electricity. To generate more electricity, multiple cells are combined in a series called a stack. However, a stack alone cannot function without the requisite components to activate and distribute power [159].

b) Fuel supply

Essentially, any material capable of undergoing chemical oxidation holds promise as a potential fuel for the anode of an FC. However, H_2 is considered the optimal option for most types of FC because of its advantageous properties, including its high energy density, strong reactivity with a suitable catalyst, and the fact that it only produces water as a by-product. While H_2 stands as the most prevalent element in the universe, it normally exists bound within compounds like water and hydrocarbons, rather than in its molecular form. In FC systems, H_2-rich gas can be generated from alternative sources like NG, petroleum, and coal, and subsequently stored within the system. Nonetheless, the storage of H_2 demands a significant amount of space, even when subjected to high pressures or liquefaction [173].

c) Oxidant supply

Theoretically, any substance capable of undergoing reduction holds the potential to be used as an oxidant. However, oxygen is the most used oxidant due to its availability in the air. In low-pressure systems, air is usually introduced using a fan or blower, while pressurised systems may require an air compressor. However, all these methods require electrical power, resulting in power loss or an additional load. In situations where minimal power is needed, like in portable devices, the utilisation of fuel cells with a passive air source becomes viable. Here, the cathode interfaces directly with the surrounding air, and oxygen replenishment relies on natural convection resulting from concentration differences. Pure O_2 systems are exclusively utilised in situations where there is no access to air, such as in submarines or space-related scenarios. This is because the storage of oxygen and the safety concerns associated with it add extra bulk and weight. In the case of FC, the supply of oxygen only necessitates a pressure regulator, given that the stored O_2 is already pressurised [174].

d) Heat and water management

The operation of FC results in the production of water & heat as by-products, which need to be removed from the system. The water can be drained while the heat can be released into the surrounding environment. However, it is possible to partially reuse both the water and heat generated by the FC stack. This can be achieved by combining water and heat management into one subsystem. In this case, the water is used to take off heat from the stack, allowing for the utilisation of the generated hot water for preheating and humidifying the reactant gases. It can also be used to produce steam for the shift reactions, as well as for reforming [159].

e) Power conditioning

The power conditioning subsystem adjusts the electricity generated by the stack to match the required voltage, power level, and transients needed for the load. Additionally, FC typically produces DC, but certain applications need AC, and a DC/AC converter is incorporated into the system. Voltage regulation plays a crucial function in this subsystem because FC stacks tend to experience voltage fluctuations that only some loads can manage. The FC system should also supply the correct voltage as well as current for its electrical components, including fans, blowers, pumps, and instruments. In hybrid configurations, the FC works in tandem with a battery or supercapacitor to handle start-up & peak power demands. The battery-produced power must also be utilised to fulfil the demands of the load. Additionally, the FC can recharge the battery as well as the super capacitor. Lastly, the power management subsystem distributes power from the FC system to the end-user, with its arrangement and attributes tailored to the particular load requirements, which can differ across applications [175].

f) Instrumentation and controls

The function of this subsystem encompasses the regulation of operational parameters within the system, including pressure, temperature, flow rates, and more. Additionally, it interacts with both the load and other electrical elements within the system, usually comprised of controllers, sensors, processors, actuators, and other components [159].

g) *Hybrid components*

In certain cases, a hybrid system is created by combining an FC with another power source. Hybridisation aims to amalgamate the strengths of each power source while mitigating their respective weakness. For instance, employing a battery enables effective handling of maximum demands & sudden changes in demand, while the FC provides the energy stored in the fuel to sustain operations [176–180]. Additionally, supercapacitor have been proposed as a supplementary power reservoir capable of integration with an FC system [181]. The supercapacitor is the same as a battery in that it is used to store electrochemical energy, but the difference is that they have a higher density of power and needs less maintenance [178–180]. In transportation demand, the FC serves as a range extender, while the purpose of a battery or supercapacitor is useful for adjusting to varying loads, recovering braking energy, and supplying start-up power. In addition, the integration of an FC stack with a heat engine, like a GT, presents the opportunity to generate supplementary power [182–188]. This arrangement is particularly advantageous, as it ensures that the temperature of the effluent streams from both the high-temperature FC stack and afterburner aligns with the desired inlet temperature for the turbine. Furthermore, various types of FC stacks can be combined in a hybrid configuration [189].

Lastly, the combination of an FC stack with renewable energy sources can enhance the advantages offered by FC technology [177,190].

5) Fuel cell types

FCs are categorised based on their electrolyte composition, which influences the chemical process, catalysts, operating temperature range, requirements of fuel, and other factors in the cell. These characteristics determine the specific applications for which each type of FC is best suited. The five primary classifications of FC encompass diverse applications [167].

a) *Proton exchange membrane fuel cell (PEMFC)*

Originating in the 1960s for the inaugural NASA Mannes space missions, this particular FC is the PEMFC, utilising a solid polymer electrolyte & operating at relatively low temperatures akin to the boiling point of water. In recent years, the PEMFC has gained considerable attention from the media, mainly because of the substantial investment made by the automotive industry in this technology. The discussion surrounding the implementation of a reformer/PEMFC system for domestic DG applications has been widely discussed due to its modular design and seemingly straightforward manufacturing process [191].

b) Solid oxide fuel cell (SOFC)

This type of FC has been available in the market since 2010. SOFC systems have a lot of advantages that give reasons for the further development of SOFC. The SOFC stands out from other FC technologies due to its reliability, high internal temperatures, high efficiency, and stability. SOFC have the capability to get around 60% of electrical efficiency and around 50% of electrical efficiency with smaller SOFC DG units. The SOFC's all-solid-state ceramic design contributes to its high stability and reliability. However, the elevated internal temperatures of the SOFC present both advantages & disadvantages. While these temperatures enable internal reforming, they also present material and mechanical design challenges, consequently diminishing longevity and elevating costs. Despite three decades of continuous research, the expenses associated with these stacks remain at relatively high levels [168,191].

c) Phosphoric acid fuel cell (PAFC)

PAFC is widely recognised as the most recognised and established FC technology. The inception of the first PAFC DG system dates back to the early 1970s. From the early 1990s onward, PAFC have been commercially available and deemed suitable for specific markets. Their deployment spans across regions, including the United States, Europe, & Japan. The available sizes of PAFC units in the market typically range from 200kW-400kW. To meet larger power needs, multiple units are typically combined. When operated under higher pressures, PAFC can achieve efficiencies of fuel-to-electricity efficiencies exceeding 40%. This innovation emerged from a collaborative effort between government and industry spanning from 1970 to 1990. In the 1990s, more than 200 commercial units were produced, supplied, & put into operation. Present-day units boast stack lifetimes exceeding 80,000 hours, with some units operating for over ten years and demonstrating reliabilities in the 90- 95% range. The main obstacle in the market has been the initial cost of installation [191–193].

d) Molten carbonate fuel cell (MCFC)

The origins of MCFC can be traced back to the early 1900s, reflecting a substantial history of development. Its operational temperature range of 600-750°C positions it favourably for CHP and distributed generation applications. This particular FC variant can incorporate internal reforming; achieving impressive efficiencies of 50% higher heating value (HHV), and it exhibits a notable tolerance to impurities in the fuel. In the 1980s and 1990s, government and industry invested in research, development, and demonstration (RD&D) programs, resulting in several demonstrations of individual pre-prototype systems. The main technical challenge of this type of FC technology lies in the degradation of cell components caused by the corrosive properties of the electrolyte at the operating temperature range [168,191].

e) Alkaline fuel cell (AFC)

F.T. Bacon showcased AFC as a functional power source in Cambridge, England during the 1940s and 1950s paved the way for its integration into NASA endeavours, such as the Apollo moon missions and subsequent space shuttle missions. AFC technology offers several benefits, including enhanced performance, utilisation of non-precious metal electrodes, & the absence of the need for uncommon materials [191]. Table 2-8 outlines the fundamental attributes associated with each type of FC.

Table 2-8: The fundamental attributes linked with each variety of fuel cell [191]

	PEMFC	AFC	PAFC	MCFC	SOFC
Type of Electrolyte	H+ ions (with anions bound in polymer membrane)	OH- ions (typically aqueous KOH solution)	H+ ions (H_3PO_4 solutions	CO3= ions (typically, molten LiKaCO3 eutectics)	0= ions (Stabilized ceramic matrix with free oxide ions)
Typical construction	Plastic, metal, or carbon	Plastic, metal	Carbon, porous ceramics	High temp metals, porous ceramic	Ceramic, high temp metals
Internal reforming	No	No	No	Yes, Good Temp Match	Yes, Good Temp Match
Oxidant	Air to 0_2	Purified Air to 0_2	Air to Enriched Air	Air	Air
Operational Temperature	150° - 180°F (65° - 85°C)	190° - 500°F (90° - 260°C)	370° - 410°F (190° - 210°C)	1200° - 1300°F (650° - 700°C)	1350° - 1850°F (750° - 1000°C)
DG System Level Efficiency, % HHV	25 to 35%	32 to 40%	35 to 45%	40 to 50%	45 to 55%
Primary Contaminate Sensitivities	CO, Sulfur and NH_3	CO, CO_2, and Sulfur	CO < 1% Sulfur	Sulfur	Sulfur

However, a major drawback is its tendency to absorb CO_2, which converts the alkaline electrolyte into a less conductive aqueous carbonate electrolyte. The popularity of AFC has significantly decreased due to the growing interest and advancements in PEMFC technology [191].

6) Thermodynamics

This section delves into the thermodynamics of a fuel cell, covering key aspects such as the enthalpy of reaction, the reversible cell potential, various voltage losses, the overall efficiency of the fuel cell, and the specific operating conditions that influence its performance.

a) Enthalpy of reaction

The amount of heat generated in a reaction hinges on the disparity in heat content between the formation of the reactants and the resulting products. For instance, the reaction between H_2 and O_2, whether it occurs through electrochemical or thermochemical means, is exothermic and produces heat:

$$H_{2\,(g)} + \frac{1}{2}O_{2\,(g)} \rightarrow H_2O_{\,(liq.)} + heat \qquad \text{Equation 2-26}$$

The determination of heat released or absorbed in a reaction entails the subtraction of the total heat of formation of the reactants from that of the products:

$$\Delta H = (h_f)_{H2O} - (h_f)_{H2} - \frac{1}{2}(h_f)_{O2} \qquad \text{Equation 2-27}$$

Where ∆H (kJ/mol) is the enthalpy change. And the enthalpy of formation, represented by h_f (kJ/kg), is the amount of heat associated with each reactant. At standard conditions (pressure = 1 atm; temperature = 25°C), the enthalpy of formation for elemental substances is typically considered zero, whereas the enthalpy of formation for liquid water is recognised as -285.8 kJ/mol:

$$\Delta H = -\ 285.8\ \frac{kJ}{mol}\ -\ 0\ -\ 0 = -285.8\frac{kJ}{mol} \qquad \text{Equation 2-28}$$

According to the sign convention, exothermic reactions have a negative heat of reaction. The heat produced by the reaction is alternatively known as the heat of combustion of H_2. When H_2 undergoes combustion with oxygen in exact stoichiometric amounts, resulting in the production of liquid water, it is identified as the Higher heating value (HHV). However, when oxygen is in surplus, the heat liberated from the combustion of H_2 is called the lower heating value (LHV), registering at -242 kJ/mol [194].

b) Reversible cell potential

The Gibbs free-energy change (ΔG) in a chemical reaction signifies the utmost energy accessible from the process. When there is no change in entropy (ΔS=0), ΔG (kJ/mol) equates to the enthalpy alteration (ΔH) of the reaction, as shown in the equation below.

$$\Delta G = \Delta H - T\Delta S \qquad \text{Equation 2-29}$$

If the ΔS (J/K) is negative, as observed in the reaction of H_2 and O_2 to form water in an FC, the change in free energy is not as pronounced as the decline in enthalpy: ΔG (kJ/mol) ≤ ΔH (kJ/mol). For the reaction between H_2 and oxygen in the liquid phase under stationary conditions (p = 1 atm, T = 25 °C), the specific values apply [195].

$$H_{2\,(g)} + \frac{1}{2}O_{2\,(g)} \rightarrow H_2O_{\,(liq.)}$$

$$\Delta G = -\,237.3\,\frac{kJ}{mol} \qquad \text{Equation 2-30}$$

The value of ΔH = -285.8 kJ/mol, as indicated in$\Delta H = -\,285.8\,\frac{kJ}{mol} - 0 - 0 = -285.8\,\frac{kJ}{mol}$ Equation **2-28**.

The alteration is Gibbs free energy is notably impacted by both temperature and the system's state (whether it is a liquid or a gas) [196]. Under ideal circumstances, such as in a reversible process, an FC does not experience any losses. Therefore, all the Gibbs free-energy alteration is transformed into electrical energy, and the reversible (or ideal) cell potential, E_r (Volts), could be calculated utilising the following equation:

$$E_r = -\frac{\Delta H - T\Delta S}{nF} = -\frac{\Delta G}{nF} \qquad \text{Equation 2-31}$$

The quantity of electrons exchanged during the reaction, denoted as 'n', equates to 2 when water is produced from the reaction of H_2 and O_2. The Faraday constant, represented as F (C/mol), has a value of 96485 C/mol. The standard-state reversible potential, E^0 (Volts), for both the half-cell reactions and the overall reaction involving H_2 and O_2, can be determined by considering the standard state (pressure = 1 atm; temperature = 25°C) [197].

Under standard conditions, a hydrogen-oxygen FC is being considered [198]:

Anode:	$H_2 \rightarrow 2H^+ + 2e^-$	$E^0_A = 0.0\ V$
Cathode:	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$E^0_c = 1.23\ V$

$$\text{Cell:}\quad H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad E^0Cell = -\frac{-237kJ/mol}{2mol.96485C/mol} = 1.229V \qquad \text{Equation 2-32}$$

c) *Voltage losses*

The effective generation of electricity from an FC requires a significant amount of current to be drawn. However, as the current increases, the actual voltage of the cell decreases compared to its reversible potential due to irreversible losses in a real-world FC. These irreversible losses, also known as over potential or polarisation, stem from three main sources:

1)- Losses in activation, denoted as ΔV_a

2)- Losses due to resistance (Ohmic losses), denoted as ΔV_O

3)- losses in mass transport or concentration, denoted as ΔV_c

Activation losses occur when the sluggish kinetics of the electrode surface control the electrochemical rate. Similarly to chemical reactions, electrochemical reaction must overcome an activation energy barrier that is determined by the surface properties of the electrode. Factors such as the adsorption and desorption of reactants and products, electron transfer across the electrochemical double layer, and the specific nature of the electrode material all contribute to this resistance, whether it exhibits a rough or smooth texture. The Tafel equation is normally used to explain the activation polarisation:

$$\Delta \boldsymbol{V_a} = \left(\frac{\boldsymbol{RT}}{\boldsymbol{a_c nF}}\right).\ln\left(\frac{\boldsymbol{i_{FC}}}{\boldsymbol{i_o}}\right) \qquad \text{Equation 2-33}$$

The equation represents the relationship between the cell's current density (i_{FC}), the reaction's exchange current density (i_0), the number of exchange protons per mole of reactant (n), Faraday's constant (F), and the charge transfer coefficient (α_c). It provides insight into how variations in applied electrical energy affect the rate of the electrochemical reaction [199].

Resistance losses occur when there is impedance to ion movement within the electrolyte materials, a phenomenon easily understood through the principles of Ohm's law.

$$\Delta V_0 = I_{FC}.\ R_{ohm} \qquad \text{Equation 2-34}$$

The text explains that I_{FC} (ampere) represents the current in the cell, while R_{Ohm} (ohm) represents the total resistance in the cell, encompassing electronic, ionic, & contact resistances. Concentration losses occur when reactants deplete quickly, fostering a concentration difference between the electrode interface and the bulk medium. Primarily stemming from the slow diffusion of reactant gases in the electrodes, but slow transport through the electrolyte also contributes. The quantification of concentration losses becomes feasible if the limiting current density, i_L, is known:

$$\Delta V_c = \left(\frac{RT}{nF}\right).\ln(1 - \frac{i_{FC}}{i_L}) \qquad \text{Equation 2-35}$$

The voltage/current relationships of PEMFC are similar in nature [194]. At low current densities, the behaviour exhibits a degree of exponential nature owing to activation polarisation involved in the O_2 reduction reaction. However, within the intermediate range of current densities, the predominant linear behaviour is attributed to Ohmic losses. At elevated current densities, the cell potential experiences swift decreases because of limitations in mass transport. The maximum voltage is attained in the absence of current flow, dictated by the standard potential of the chemical reaction (as indicated in equation 2-59 with a value of 1.23 V under standard conditions). Nonetheless, in real-world scenarios, the voltage at zero current, known as the open-circuit potential, typically stabilises slightly lower, around 1 V. This divergence could be described by taking the open-circuit potential as a mixed potential, because of the concurrent incident of the four-electron & two-electron oxygen reduction reactions. The two-electron reaction involves a stepwise reduction through hydrogen peroxide as an intermediate. Additionally, the involvement of impurity oxidation might play a role in this discrepancy. Both electrodes can experience activation polarisation and concentration losses. Polarisation causes a shift in the electrode potentials, resulting in altered values. Therefore, the voltage at the anode (cathode) can be understood as the reversible electrode potential augmented (diminished) by electrode polarisation [200].

$$VA_{(C)} = E_{A(C)} \pm I\Delta V_{a,A\,(C)} + \Delta V_{c,A(C)} l \qquad \text{Equation 2-36}$$

The cell's overall voltage, V_{FC}, results from the differences between the anode and cathode voltages, while the Ohmic losses occurring within the cell [196].

$$V_{cell} = V_C - V_A - \Delta V_0 \qquad \text{Equation 2-37}$$

and therefore, equivalent to:

$$V_{cell} = (E_C - I\Delta V_{a,C}\, I) - \ I\Delta V_{c,C}\, I\ ) - (\ E_A -\ I\Delta V_{a,A}\, I - I\Delta V_{c,A}\, I\ ) - \Delta V_o \qquad \text{Equation 2-38}$$

d) Efficiency of the fuel cell

Thermodynamic efficiency, denoted as η_{id}, characterises the maximum efficiency attained under reversible conditions. An FC could be delineated as the ratio of the ideal electrical work to the entirety of energy potentially liberated by the reaction:

$$\eta_{id} = \frac{\Delta G}{\Delta H} \qquad \text{Equation 2-39}$$

In this scenario, the FC operates perfectly, allowing for the complete conversion of the free-energy change into electrical energy. By utilising HHV of H_2, a maximum efficiency of 83% can be achieved [200].

The voltage efficiency, denoted as η_{cell}, serves as a metric for assessing the performance of FC & is instrumental in comparing various cell designs. It is defined as follows [201].

$$\eta_{cell} = \frac{-nF.V_{cell}}{\Delta H} = \frac{V_{cell}}{E_{th}} \quad \text{Equation 2-40}$$

The theoretical standard electrode potential, denoted as E_{th}, is determined by the enthalpy change. E_{th} can be associated with the heating value of the fuel, and when LHV is utilised, the voltage efficiency is referred to as V_{LHV} (Volts). Whereas, if the HHV is taken into account, it is called V_{HHV}:

$$\eta_{cell} = \frac{V_{cell}}{V_{LHV}}, \quad \text{using LHV} \quad \text{Equation 2-41}$$

$$\eta_{cell} = \frac{\boldsymbol{V_{cell}}}{\boldsymbol{V_{HHV}}}, \quad \text{using HHV} \quad \text{Equation 2-42}$$

In relation to the reaction between H_2 and O_2, the voltage for V_{LHV} is 1.23 V, whereas for $V_{HHV,}$ it is 1.48 V [195,202].

The faradaic efficiency, denoted as η_f, represents the correlation between the measured current, I_{FC} (Amp), and the anticipated current, I_{id} (Amp), based on the flow of H_2 entering, assuming that all H_2 is used up.

$$\eta_f = \frac{I_{FC}}{I_{id}} \quad \text{Equation 2-43}$$

The efficiency of the faradaic process may be lower than one because of factors such as limited use of H_2, simultaneous electrochemical reactions, and the crossover of H_2 [203].

The fuel utilisation factor, also known as U_f, is a measure of the ratio between the amounts of fuel (H_2) that is actually reacted (m_i) in the electrochemical reactions relative to the total amount of hydrogen fuel (m_{H2}) that is supplied into the cell.

$$U_f = \frac{m_i}{m_{H2}} \quad \text{Equation 2-44}$$

The efficiency of the cell can be represented as the multiplication of the two factors, as follows [194]:

$$\eta_{cell} = \eta_{id}.\,\eta_V.\,U_f \quad \text{Equation 2-45}$$

e) Operating condition

The primary operating parameters of a PEMFC system include pressure, temperature, and relative humidity, all of which significantly influence the cell's performance, efficiency, and durability. This section summarizes the operational conditions reported in the literature, along with ideal parameters for optimal performance, as shown in the following Table 2-9 [194].

Table 2-9: Primary operating parameters of a fuel cell [194]

Operating parameter	Range	optimal
Fuel	H_2	H_2 - 99.99995 %
Oxident	O_2 or air	O_2
Temperature	20°C - 90 °C	60 °C - 80 °C
Pressure	1 - 3 atm	2 - 3 atm
Relative Humidity (RH)	50 - 100 %	100 %

According to the above table, the temperature range spans from 20 to 90°C. It's a common understanding that elevated temperatures generally enhance FC performance. However, the upper-temperature limit is determined by the glass transition temperature of the polymer membrane commonly used in PEMFC. Additionally, the moisture content within the membrane exerts a notable influence on its proton conductivity, which further limits the temperature range. However, it may not be beneficial for the design of the FC system to rely on high operating temperatures. Most PEMFC typically operate within a pressure range of 1 to 3 atm. FC that run at 3 atm necessitate extra equipment for pressure control and monitoring. Therefore, operating the FC system above atmospheric pressure might not yield significant benefits. It is important to monitor the relative humidity daily as it fluctuates under normal conditions. Additionally, it is important to monitor and regulate the humidity, temperature, pressure, & flow rates of H_2 and oxidants based on the surrounding conditions and the needs of the system [194].

7) Application and the characteristics

This section offers an in-depth exploration of the various applications and key characteristics of fuel cells, highlighting their underlying operational principles, performance advantages such as high efficiency and low emissions, and their suitability across diverse sectors including transportation, stationary power generation, and portable devices.

a) Applications

FC systems are expensive to install, the most common and cost-effective use of distributed generation (DG) is CHP. CHP involves producing power on-site while also utilising the heat produced as a by-product. Operating continuously and effectively utilising the thermal energy from emissions and cooling systems enhances the economic viability of on-location power production. Typically, heat is recuperated from FC in the guise of hot water or low-pressure steam, further bolstering the system's overall efficiency. The heat quality is determined by the specific FC type and its operational temperature. Two types of FC, including PEMFC and DMFC, run at below T=200°F, resulting in low-quality heat. This heat is applicable for various uses including low-temperature processes, heating potable water, & space heating. In contrast, methods like SOFC and MCFC can produce medium-pressure steam by harnessing high-temperature exhaust gas from the FC. However, the main purpose of this hot exhaust gas is to facilitate heat exchange with incoming process gases through recuperative heat exchange. Hot water remains the easiest type of thermal load to provide. CHP is commonly utilised in commercial and institutional buildings with substantial demands for both electricity and hot water/space heating. This includes educational institutions such as schools, colleges, and universities, as well as healthcare facilities like hospitals, and nursing homes, along with hotels. Advancements in heat-activated cooling/refrigeration and thermally regenerated desiccants will further improve the use of FC-based CHP systems in certain buildings by increasing the demand for thermal energy. By incorporating these innovative solutions, establishments like restaurants, supermarkets, and refrigerated warehouses can also benefit from CHP by utilising their base-thermal load [204].

b) Characteristics

In the characteristics of a fuel cell section, covers performance attributes, emission characteristics, and the general features of a fuel cell.

- *Performance characteristics*

The performance of an FC depends on its type and capacity. The FC system consists of various subsystems, and these subsystems are components of electronic, chemical, and electrochemical. Optimising the efficiency and performance of such systems often presents a challenging engineering endeavour. Nonetheless, successful FC systems such as PEMFC and SOFC have been introduced specifically for micro-CHP applications (below 10 kW), catering to residential, domestic, and small commercial buildings. These systems are commonly used in Europe & Asia, and these systems have gained traction. In the US, most FC-based CHP systems employ two types of technologies, including MCFC and PAFC, and these technologies are designed for large institutional and commercial buildings. Table 2-10 outlines the performance attributes of three FC-based CHP systems, which differ in scale, ranging from 300 kW to 1400 kW [205].

Table 2-10: Characteristics of fuel cell performance [205]

Description	System		
	1	2	3
Net Electric Power (kW)	300	400	1400
Fuel Cell Type	MCFC	PAFC	MCFC
Fuel	Natural Gas	Natural Gas	Natural Gas
Fuel Input (MMBtu/hr, HHV)	2.41	3.59	11.24
Useful Thermal (MMBtu/hr)	0.79	0.88	3.63
Power to Heat ratio	1.3	1.55	1.31
Electric Efficiency (%, HHV)	42.50%	38.00%	42.50%
Thermal Efficiency (%, HHV)	32.70%	24.50%	32.30%
Overall Efficiency (%, HHV)	75.20%	62.50%	74.80%

PAFC systems run at temperatures between 150 to 200 °C, whereas MCFC applications run at elevated temperatures ranging from 600 to 700 °C. PAFC systems normally utilise thermal energy to produce hot water or low-pressure steam of low pressure, while MCFC systems can produce low or medium-pressure steam in addition to hot water. The economic viability of FC in on-location power production is less reliant on effectively using recaptured thermal energy compared to less efficient prime movers. However, in any CHP scenario, displacing thermal load could enhance the operating efficiency of an FC system. Normally, around 25 percent of the fuel's input energy can be reclaimed as high-quality heat from the stack and reformer units, while an additional 25% is found in the exhaust stream, which also includes the latent heat from the water produced during fuel cell operation. This recovered heat is commonly used for producing hot water or low-pressure steam, essential for space heating or industrial applications. The grade of the recovered heat is contingent upon the type of FC & its operational temperature, yet it is generally attainable as hot water or steam at low-pressure below 30 psig [168,205].

- *Emissions characteristics*

A FC stack converts fuel into electricity through an electrochemical process, without producing harmful substances like nitrogen oxides (NOx), carbon monoxide (CO), or volatile organic compounds (VOCs). While FC reformers necessitate combustion, their emissions are minimal. The FC stack generates anode off-gas, which contains 8 percent to 15 percent H_2. This H_2 is burned within the reformer utilising either a catalytic or surface burner running at a temperature under T=1800° F. This temperature is high enough to oxidise CO and VOC emissions, but low enough to minimise the formation of NOx. FC, like other CHP technologies that utilise NG, generates CO_2 emissions. Table 2-11 displays the correlation between CO_2 emissions, electric power output, and the extensive performance of the CHP system [205].

Table 2-11: Characteristics of emissions from fuel cells [205]

Description	System		
	1	2	3
Net Electric Power (kW)	300	400	1400
Fuel Cell Type	MCFC	PAFC	MCFC
Emissions (lbs/MWh, based on electric power only)			
NOx	0.01	0.01	0.01
CO	0.02	0.02	0.02
VOCs	0.02	0.02	0.02
CO_2 Emissions (lbs/MWh)			
Electric Power Only	939	1,050	939
CHP with Thermal credit?	555	729	559

To evaluate the efficiency of FC-based CHP systems, CO_2 emissions are calculated by considering the NG fuel consumption equivalent to that of an on-site boiler. The calculation results in CO_2 emissions ranging from 555 to 729 lbs/MWh for the three representatives of FC-based CHP systems. By contrast, a conventional NG combined cycle power plant emits between 800-900 lbs/MWh, whereas a coal-fired plant emits approximately 2000 lbs/MWh of CO_2. It is worth noting that FC systems typically do not need additional emissions control instruments to comply with existing and future regulations. Additionally, FC normally have very low emissions [205]. Table 2-12 presents the overall attributes of fuel cells, including various efficiencies (electrical, thermal, and overall), power-to-heat ratio, Combined Heat and Power installation cost, maintenance requirements, availability, overhaul intervals, NOx emissions, available capacities, fuel types, thermal output applications, power density, system sizes, noise levels, part-load performance, payback period, and CO_2 emissions.

Table 2-12: Characteristics of the fuel cells

Characteristic	Fuel Cells	Characteristic	Fuel Cells
Electric efficiency (HHV)	30-63% [98]	Available sizes	5 KW to 2.8 MW [206]
Overall efficiency	88 - >95 [207,208]	Fuel pressure (psig)	0.5-45 [98]
Effective electrical efficiency	55-80 [98]	Fuels	hydrogen, natural gas, propane, methanol [98]
Power to heat ratio	1-2 [98]	Applications of thermal output	warm water, steam generation [98]
CHP Installed cost ($/KWe)	5000-6500 [98]	Power density (KW/m^2)	5-20 [51]
Non-fuel O&M costs ($/KWe)	0.032-0.038 [98]	Size (m^3)	1.26 [98]
Availability	99% [98]	Noise	Low [146]
Hours for overhauls	32000-64000 [98]	Part Load	Good [98]
Start-up time	3 h-2 days [98]	Payback period	10 years [59]
NOx (kg/MWhe)	0.011-0.016 [98]	CO_2 (lb/MWhe)	980-998 [145]

8) Current state of the art

In the past decade, the majority of research on micro-CHP systems has focused on the FC. Currently, different FC technologies are available in the market, along with different sizes and unique designs. PEMFC and SOFC are the key players in the residential CHP systems [158,159]. Several major companies have been involved in the current market of FC-based micro-CHP systems, and their products have been tested in several countries, including Japan, South Korea, and Germany on a large scale [158]. One example is Sulzer Hexis, a European company that has tested over 100 SOFC systems for domestic applications in Europe. On the other hand, Kyocera, a Japanese company, manufactured a 1-kilowatt micro-CHP system based on SOFC. In both SOFC and PEMFC, there are still numerous technical challenges. The tubular SOFC technology has demonstrated durability of over 70,000 hours for a single cell and over 20000 hours for a 200-kilowatt power plant. However, the planar SOFC system is still being developed & faces challenges related to interconnect longevity, seal integrity, & resistance to thermal cycling. Regarding PEMFC, the membrane has a relatively short lifespan, and achieving the desired durability of 40,000 hours currently lacks a clear solution [60].

9) List of commercially available fuel cells

Table 2-13 offers a detailed summary of commercially available fuel cells, emphasising their key features, including brand, model, type, electrical power output, electrical efficiency, overall efficiency, and dimensions.

Table 2-13: Commercially available Fuel cells and their specifications [102][149][207][208][209][210][211]

Brand	Model	Types	Electrical Output (kW)	Electrical Efficiency (%)	Overall efficiency (%)	Dimensions (mm) (WxDxH)
BlueGen [207]	BG-15	SOFC	1.5	55	88	550x800x1200
Elcore [209]	Elcore 2400	HTPEM technology	0.3	32	-	600x550x1050
Elcore [210]	Vitovalor 300-P from Viessmann	Low temperature PEM	0.75	37	> 90 (at trl <40 ° C)	600x595x1932
Hexis [208]	Galileo 1000 N	SOFC	1	35	95	620x580x1640
Kd fuel cell [102]	IRD Fuel Cell	PEM	1.5	-	94	-
Baxiinnotech [149]	Gamma 1.0	PEM	1	32	>95	600x600x1600
Viessman [211]	Vitovalor PT2	PEM	0.75	37	92	1200x595x1800

10) Fuel flexibility OR Fuel for a fuel cell

H_2, which is used as fuel in FC, cannot be found naturally in its pure state. It must be extracted from chemical compounds through methods like electrolysis from water or chemical methods from hydrocarbons or alternative H_2 carriers like NG, diesel, methanol, gasoline, or gasified coal. Figure 2-21 illustrates the various fuel processing methods for each type of FC. It is evident that as the temperature and efficiency of the FC decrease, the fuel processing becomes increasingly intricate [167].

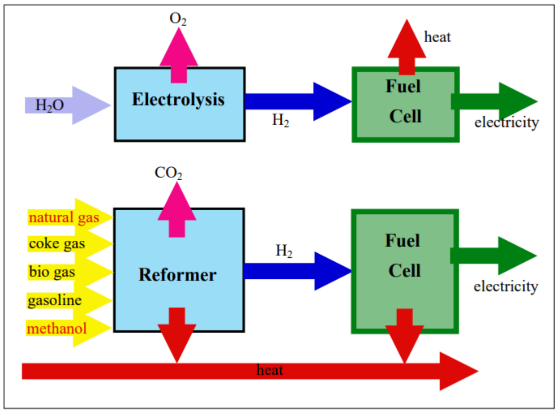

Figure 2-21: Basic schematic of a fuel cell setup [167]

11) Benefits and limitations

Table 2-14 provides a comparison of fuel cell applications, along with their advantages and disadvantages.

Table 2-14: A comparison of fuel cell applications, benefits, and drawbacks [98]

Fuel Cell Types	Applications	Advantages	Disadvantages
Alkaline Fuel Cell (AFC)	· Military	· Cathode reaction faster in alkaline electrolyte, leads to high performance.	· Sensitive to CO2 in fuel and air
	· Space	· Low-cost components	· Electrolyte management
Direct Methanol Fuel Cell (DMFC)	· Backup power	· No need for reformer (catalyst separates H_2 from liquid methanol)	· Expensive catalysts
	· Portable power	· Low temperature	· Low-temperature waste heat
	· Military		
Phosphoric Acid Fuel Cell (PAFC)	· Auxiliary power	· Higher temperature enables CHP.	· Platinum catalyst
	· Electric utility	· Increased tolerance to fuel impurities	· Startup time
	· Distributed generation		· Low current and power
Proton Exchange Membrane Fuel Cell (PEMFC)	· Backup power	· Solid electrolyte reduces corrosion & electrolyte management problems.	· Expensive catalysts
	· Portable power	· Low temperature	· Sensitive to fuel impurities
	· Distributed generation	· Quick startup	· Low-temperature waste heat
	· Transportation		
	· Specialty vehicles		
Molten Carbonate Fuel Cell (MCFC)	· Auxiliary power	· High efficiency	· High-temperature corrosion and breakdown
	· Electric utility	· Fuel flexibility	· Long startup time
	· Distributed generation	· Can use a variety of catalysts.	· Low power density
		· Suitable for CHP	
Solid Oxide Fuel Cell (SOFC)	· Auxiliary power	· High efficiency	· High-temperature corrosion and breakdown of cell components
	· Electric utility	· Fuel flexibility	· High temperature operation requires a long startup time and limits
	· Distributed generation	· Can use a variety of catalysts.	
		· Solid electrolyte	
		· Suitable for CHP & Combined heat, hydrogen, and power Hybrid/GT cycle	

FC offers several advantages, including higher efficiency, lower emissions, etc. compared to other prime movers of a CHP system. Maintenance is required for certain components, such as pumps and blowers, but overall upkeep is relatively low. However, there are also notable limitations to FC stacks. SOFC operate at high temperatures, resulting in slower response times, making them more appropriate for continuous power production. Conversely, PEMFC operates at lower temperatures, allowing for better performance at varying loads and faster response times. However, PEMFC have a shorter membrane lifespan. Additionally, FC in general are expensive to produce [60]. The overall benefits and limitations of fuel cells are outlined in Table 2-15.

Table 2-15: Advantages and disadvantages of fuel cells [98]

Advantages	Disadvantages
Low emissions	High costs
High efficiency across a wide load range	Fuels need processing unless pure hydrogen is used
Modular construction	Prone to fuel contamination
Minimal noise output	Lower power density

12) Market analysis / Market size

In 2020, the FC market had a value of $3.6B, with forecasts suggesting it will reach $32.0B by 2030, demonstrating a notable compound annual growth rate of 19.4% from 2021 to 2030 [212]. The Figure 2-22 shows the FC market from 2020 to 2030.

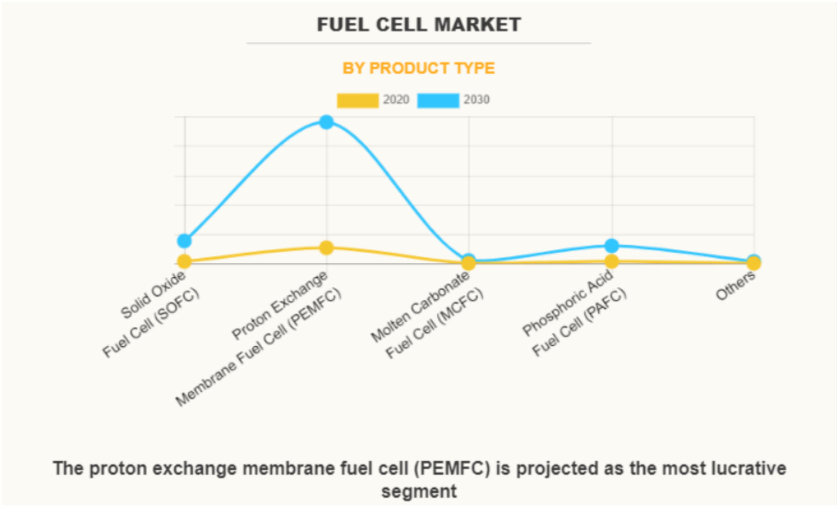

Figure 2-22: Fuel cell market trends (2020-2030) [212]

The COVID-19 pandemic inflicted adverse effects on the global FC market, resulting in disruptions across industries, manufacturing, & supply-demand imbalances. This resulted in a decrease in demand for FC in 2020. The lockdown measures implemented during the pandemic temporarily halted import-export activities and manufacturing and processing operations in various industries and electrical utilities, further reducing the demand for FC from these consumers. The FC market report from 2021-2030 is examined based on the effects of the factors that drive, limit, and provide opportunities [212]. The PEMFC segment dominated the FC market in 2020 due to an increase in the demand for clean power generation [212].

13) Future industry and technology trends

A primary drawback of FC is its expensive initial investment. Manufacturers of FC are trying to improve the economic viability by incorporating them into CHP applications. The success of micro-CHP applications with FC depends on cost reduction per unit, which can only happen with increased sales. The first step towards this goal is to overcome technological challenges, such as ensuring stable performance and durability under thermal cycling conditions, especially for SOFC. According to the estimates, the commercialisation of FC-based micro-CHP systems may take several years. The focus of development work is expected to be on improving the FC stack, rather than the design of the CHP system. This preference stems from the perception that the heat recovery devices necessary for the system are not particularly unique or challenging [60].

14) Future developments

In recent years, there has been a decline in the price of FC technology, and its use has increased in various systems. In the US, several factors indicate a continued growth in the FC market. These factors include on-going advancements in FC technology that reduce costs, the emergence of novel business models like leasing arrangements, supportive incentives and policies, and a persistent demand for low-emissions solutions. Additionally, the overall advantages of distributed energy in terms of resilience and reliability [205].

2.2.4 Micro-gas turbines (MGT)

Micro-gas turbine (MGT) is one of the main prime movers in a micro-CHP system [213]. It represents advanced innovation characterised by rapid load response and a straightforward structure [214]. MGT can run on several fuels including NG, hythane, biogas, kerosene, biodiesel, and associated gas, etc. [213]. These systems could be integrated with additional energy consumption apparatus or recycling systems, like SOFC and Organic Rankine cycle units [215]. Figure 2-23 illustrates the schematics of an MGT engine.

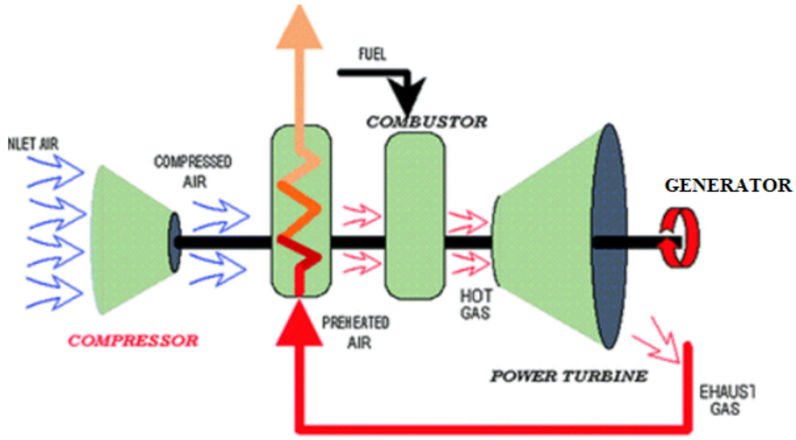

Figure 2-23: Diagram of a micro-gas turbines engine [71]

In recent decades, the development of MGT systems has accelerated because of their small footprint, quiet operation, economic viability, low carbon footprint, and adaptable performance [215]. While the electrical efficiency of MGT remains relatively low (between 15% and 25%), it can improve with the use of recuperated systems. On the other hand, thermal efficiency typically exceeds 70%, making them ideal for small-scale applications [213]. These systems can achieve overall CHP efficiencies exceeding 94% [215].

1) Brief history of an MGT

The inception of micro-gas turbines (MGT) technology traces back to the 1950s, with the automotive industry leading the research. They were exploring the possibility of using MGT instead of ICE. This was because MGT offered benefits including minimal pollutant emissions and adaptable operating capabilities and fuel usage. In the early 1980s, the technology became more suitable for practical use with the introduction of permanent magnets as high-speed generators. These generators, which use permanent magnets for field excitation, are small, lightweight, reliable, efficient, and require low maintenance. This made them a favourable choice to integrate with MGT. However, despite the use of permanent magnet generators, the hybrid-electric drivetrain technology remained insufficiently developed, leading to a lack of significant success for MGT within the automotive industry. During the latter part of the 1980s, there was a surge in demand for MGT, which gained momentum throughout the 1990s because of the rising fascination with distributed power generation. By the later part of the 1990s, the expanding demand for hybrid vehicles further sparked interest in MGT. These turbines were integrated with electric motors to produce propulsion force. Simultaneously, the deregulation of the electricity market started to become deregulated in the later part of the 1970s in the US and several European nations. Promoting MGT aimed to disrupt the prevailing monopoly within the electricity generation industry, thereby catalysing the growth of decentralised power generation. The research and development sector became interested in MGT owing to their promise and significance within the emerging decentralised electricity market. During the 1980s, efforts were underway to develop a 50-kW GT equipped with a cogeneration heat recovery system within the framework of the Advanced Energy System (AES) program. However, the initiative was discontinued during the 1990s owing to the excessive final expenses associated with the product. In 1988, a Capstone turbine was established under the name of NoMac Energy Systems. They began working on the MGT concept in the later part of the 1980s and conducted field tests for a 24-kW engine in 1997, followed by the introduction of the commercial product in 1998. During the latter part of the 1990s, MGT gained popularity in demand in the distributed power generation industry. By the year 2000, MGT had achieved electrical efficiency ranging from 23- 30% and an overall efficiency of 65-75% in cogeneration mode. Since then, several companies from the US, England, and Sweden have emerged, offering different power outputs for installation in microgrids or hybrid cars. These enterprises include Aurelia, Elliott Energy Systems, Browman Power, Capstone, Turbec, AlliedSignal, and ABB Distributed Generation in collaboration with Volvo Aero Corporation [216,217].

2) MGT components

The fundamental elements of the MGT system are the combined compressor/turbine unit, recuperator, generator, combustor, and CHP heat exchanger. Further elaboration on each of these main elements will follow [213,218].

a) Turbine & compressor

The core component of the MGT consists of the compressor-turbine unit, typically installed on a unified shaft alongside the electric generator. This shaft rotates at speeds exceeding 60000 rpm and is sustained by either air bearings or traditional lubricated bearings. The one-shaft design, with its sole moving part, holds promise for decreasing maintenance requirements and improving overall dependability. MGT utilises single-stage radial flow compressors and turbines, which differ from larger turbines that employ multi-stage axial flow configurations. Radial turbo machinery is known for its ability to efficiently handle modest volumetric flows of air and combustion by-products. In comparison, larger axial flow turbines and compressors tend to exhibit higher efficiency than radial flow components. However, for MGT operating within the range of 0.5-5 lbs/sec of air/gas flow, the use of radial flow components can minimise losses at the surface and end wall, ultimately leading to improved efficiency [218,219].

b) Generator

The MGT can generate electricity in two ways: either by employing a high-speed generator connected to the turbo-compressor shaft or by utilising a speed reduction gearbox to drive a standard generator operating at 3,600 rpm. The majority of MGT power electronics produce three-phase electricity. In a single-shaft design, the generator functions as a motor, and rotates the turbo-compressor shaft until it reaches the required rpm to initiate the combustor. During operation without a connection to the power grid (known as black starting), it depends on a power storage system, usually a battery, to provide power to the generator during the start-up process. Electronic components oversee the system's operations and start-up procedures. Management units typically have controls that enable them to function either in parallel with or separately from the power grid. They also include various grid and system protection functionalities necessary for interconnection. Additionally, they facilitate remote monitoring and operation through integrated controls [218].

c) Recuperator & combustor

The heat exchanger known as the recuperator utilises the high-temperature exhaust gas from the turbine (usually at approximately 1200ºF) to preheat the compressed air (usually approximately 300ºF) prior to its entry into the combustor. This preheating process helps to reduce the quantity of fuel necessary to raise the compressed air to the requisite turbine temperature. While recuperator hold the potential to significantly increase the machine's efficiency, sometimes even doubling it, contingent upon the operating conditions of the MGT. However, this enhanced efficiency comes with a trade: a reduction in power output of approximately 10-15 percent, owing to heightened pressure losses experienced on both the compressed air inlet and turbine exhaust outlet of the recuperator [218–220].

d) CHP heat exchanger

In the operation of CHP, MGT provides an extra heat exchanger module seamlessly incorporated into the primary setup. This package is designed to efficiently harness a significant amount of the residual energy in the turbine's exhaust stream, typically maintaining a temperature range of 500-600 ºF. The heat produced by the exhaust holds multifaceted utility, serving purposes including water heating, space warming, & operating cooling and dehumidification systems like absorption chiller and desiccant dehumidifiers. Moreover, the clean exhaust from MGT, boasting notable oxygen content (around 15%), can be directly employed for industrial processes. For instance, it can power an absorption chiller with a double effect or supply preheated air for combustion in a boiler or other heat-related applications [218,221].

3) MGT types

Gas turbines (GT) can be classified into three distinct types according to the number of spools they possess single-spool, dual-spool, or triple-spool configurations [222].

a) Single-shaft gas turbine

The single-shaft GT consist of a single shaft that connects the compressor & turbine. This configuration enables the compressor to intake air, elevating its pressure by mixing it with fuel, thereby generating by-products at an elevated temperature. The ensuing hot flue gas, a product of combustion, is directed into a turbine to generate power. A portion of this power propels the compressor via the shift, while the remainder drives a generator for the purpose of electricity generation [223]. The classification of a single shaft GT can depend on the type of compressor used, which may be either a dual compressor or a single compressor [223].

b) Dual shaft gas turbine with a power turbine

The initial turbine is utilised to power the compressor, while the second turbine is employed to power the load. Known as the free turbine, the power turbine is mechanically separate and drives the load. The gas generator encompasses the remaining components: the turbine, compressor, combustor, & high-pressure turbine [222].

The initial compressor, known as the low-pressure compressor (LPC), is positioned beside the intake. It is linked to the Low-pressure turbine (LPT) and is powered by it. The High-pressure compressor (HPC) is attached to the High-pressure turbine (HPT), and its shaft is aligned with the low-pressure shaft [223].

c) Triple shaft gas turbine with a power turbine

A GT featuring three shafts comprises a low-pressure (LP), intermediate-pressure (IP), & and high-pressure (HP) shaft, each circulates at varying speeds. The fan is linked to the LPT through the LP shaft [222]. The intermediate shaft serves to connect the compressor and turbine that operate at IP levels, while the HP shaft links the HP compressor and turbine [224].

All kinds of GT possess both benefits and drawbacks. Table 2-16 provides a comparison between single-shaft, dual-shaft, and triple-shaft gas turbines

Table 2-16: Contrast of GT engines based on the shaft count [225]

Types	Pros	Cons
Single-shaft GT	• The simplest design option • Low upkeep • Avoiding excessive speed situations caused by the compressor's high-power demand can serve as a reliable brake in the event of an electrical load loss	• Needs a substantial initial device • Restricted speed range • Efficiency is low
Dual-shaft GT	• High Efficiency • Wide range of speeds • Requires a compact starting apparatus • The gas generator speed fluctuates based on the electrical load • Lower initial power demands • Improved effectiveness in non-standard conditions	• A control system that is more intricate • Higher maintenance requirements • If the electrical load is reduced, it can cause the power turbine to exceed its normal speed
Triple-shaft GT	• Efficiency is high • Wide range of speeds • Needs a smaller device to initiate • Reduced power needed for starting as only the HPC and HPT in the gas generator are activated • GTs used in aircraft are known as aero derivative	• A control system that is more intricate • Higher maintenance requirements

4) Analysing the thermodynamic characteristics of the ideal cycle and deviations from ideal behaviour

A GT operates using the open Brayton cycle, which involves four key ideal processes: an isentropic compression to reach the cycle’s peak pressure, followed by an isobaric compression to reach the cycle’s peak temperature, and then followed by isentropic expansion down to the lowest pressure point, concluding with heat rejection at constant pressure. The schematic on the left side of Figure 2-24-left illustrates the arrangement of a perfect basic GT that includes an external heat source (without a combustion chamber). In Figure 2-24-right, the T-S diagram is presented, illustrating the characteristics of air with a molecular mass of 29kg/kmol. The diagram depicts a pressure ratio of 5, an ambient air temperature of 5ºC, and a TIT of 1000ºC [226,227].

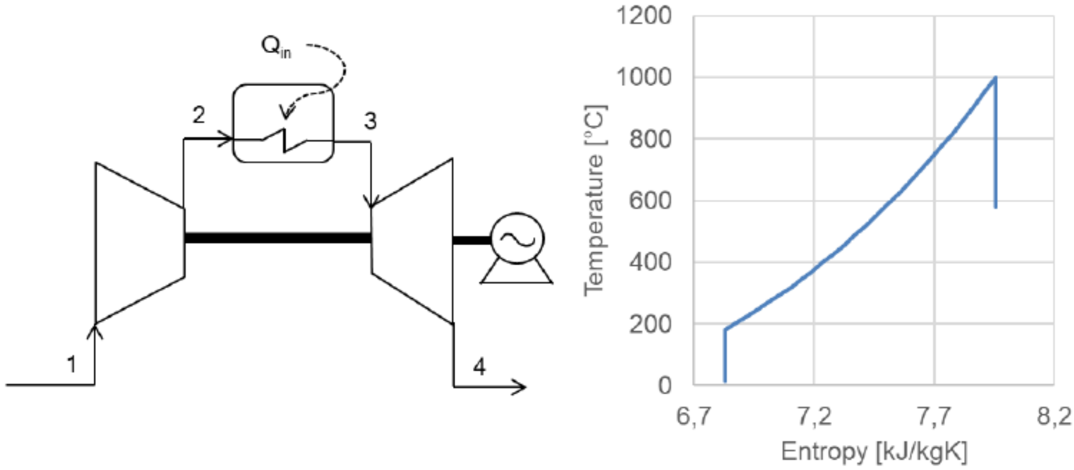

Figure 2-24: Optimal simple GT layout (left) and T-S diagram (right) [226]

The regenerative GT is an improved version of the basic cycle by capturing residual heat from the turbine exhaust to preheat the compressed air prior to combustion. This process reduces the external heat input needed. Figure 2-25-left shows the Ideal regenerative GT layout, while Figure 2-25-right depicts the T(ºC) - S(kJ/kg·K) diagram, assuming the same conditions as the simple cycle, assuming perfect regeneration. In this thermodynamic process, the high-temperature fluid undergoes a cooling process until it reaches the inlet temperature of the low-temperature fluid. Simultaneously, the low-temperature fluid is subjected to a heating process until it attains the inlet temperature of the high-temperature fluid at the regenerator. The T-S diagrams confirm that although the network output remains the same, but the regenerative case requires less heat input, resulting in higher efficiency [59,226].

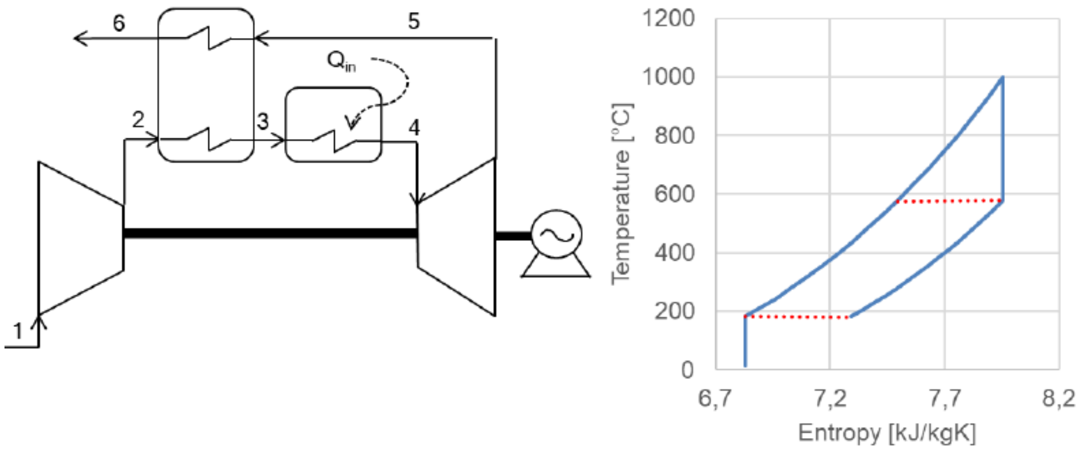

Figure 2-25: Optimal regenerative GT layout (left) and T-S diagram (right) [226]

Following the qualitative assessment of the cycle's performance, the subsequent analysis will concentrate on assessing the efficiency of both cycles. The alteration in entropy of a fluid could be described by the equation, assuming it behaves as a perfect gas with specific heat (c_p) in J/(kg·K) & gas constant (R*) in J/mol·K:

$$ds = c_P\,(\frac{DT}{T}) - R^*(\frac{dp}{p})$$ Equation 2-46

By defining Θ as $$\Theta = \frac{R^*}{C_P}$$ Equation 2-47

In the case of isentropic conditions, one can determine the outlet temperature post-compression by using Equation 2-47 and, following expansion Equation 2-48 can be utilised. Here β represents the pressure ratio between the outlet pressure & inlet pressure.

$$T_{out,\,comp} = T_{in,\,comp}\beta^{\Theta}$$ Equation 2-48

$$T_{out,\,turb} = T_{in,\,turb}\beta^{-\Theta}$$ Equation 2-49

The efficiency (η) of a basic gas turbine operating with an ideal gas is characterised by the quotient of the obtained (l_{net}) network to the input heat of the system (q_{in}):

$$\eta_{simple} = \frac{I_{net}}{q_{in}} = \frac{C_p\,(T_3-T_4)-C_p\,(T_2-T_1)}{C_p\,(T_3-T_2)} = 1 - \frac{T_4-T_1}{T_3-T_2}$$ Equation 2-50

Given that the turbo machinery operates under isentropic conditions, it can be represented as:

$$\eta_{simple} = 1 - \frac{T_3\beta^{-\Theta}-T_1}{T_3-T_1\beta^{\Theta}} = 1 - \beta^{-\Theta}$$ Equation 2-51

The efficiency of a regenerative Joule-Brayton cycle employing an ideal gas as the working fluid can be represented as:

$$\eta_{regenerative} = \frac{I_{net}}{q_{in}} = \frac{C_p\,(T_4-T_5)-C_p\,(T_2-T_1)}{C_p\,(T_4-T_3)} = 1 - \frac{T_2-T_1}{T_4-T_3}$$ Equation 2-52

And if assume that the conditions are isentropic, it can be written as:

$$\eta_{regenerative} = 1 - \frac{T_1\beta^{\Theta}-T_1}{T_4-T_4\beta^{-\Theta}} = 1 - \frac{T_1}{T_4}\beta^{\Theta}$$ Equation 2-53

Examining Equation 2-50, it becomes evident that the efficiency of a perfect GT functioning on a fundamental cycle is solely determined by the pressure ratio and the fluid being used. If the pressure ratio increases, the efficiency also increases. In contrast, Equation 2-52 demonstrates that the efficiency of an ideal regenerative GT is influenced by the pressure ratio, along with the inlet and maximum temperatures. Unlike the simple GT, a rise in the pressure ratio results in a reduction in efficiency, while conversely, an increase in the maximum temperature corresponds to a boost in efficiency. The graph in Figure 2-26, illustrates the efficiency's variation concerning the pressure ratio on the left side and the net-specific work on the right side. This is shown for two distinct maximum temperatures: 800ºC positioned at the top and 1000ºC located at the bottom. The representation includes both a simple gas turbine (represented by black lines) and a regenerative GT (represented by blue lines). The solid lines depict ideal scenarios, while the dashed lines illustrate a more realistic behaviour, taking into account an isentropic efficiency of the turbo machinery of 90%, a pressure drop of 2% across the heat exchangers compared to the inlet pressure, and a regenerator effectiveness of 90% [226].

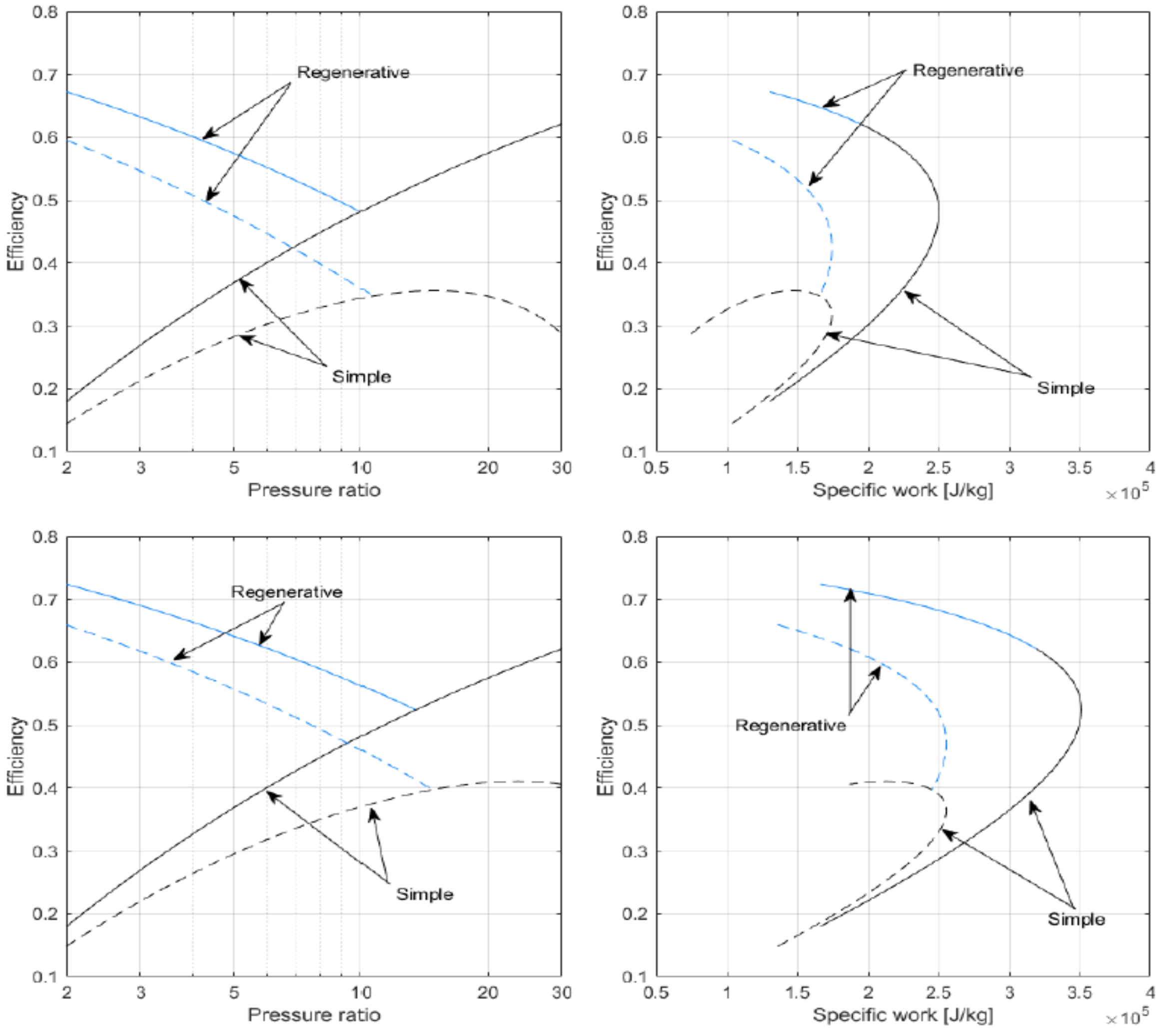

Figure 2-26: Graph of Efficiency vs. Pressure Ratio (left) and Graph of Efficiency vs. Specific Work (right) [226]

As previously predicted, the efficiency of the ideal simple GT remains constant regardless of the maximum temperature, yet the specific work 'w' (J/kg) escalates as the temperature rises. Conversely, in the scenario of a regenerative GT, efficiency decreases as the maximum temperature decreases. When considering real conditions, the maximum temperature has an impact on the efficiency of the simple GT, with higher temperatures correlating to heightened efficiency. The pressure ratio also affects the efficiency of both cycles. As mentioned earlier, efficiency diminishes with the pressure ratio for the ideal regenerative GT, while it ascends for the ideal simple GT. Nonetheless, various losses can alter this behaviour in the latter case, indicating an optimal pressure ratio that maximises efficiency. Furthermore, the w_{net} rises as the maximum temperature increases for both cycle layouts [226].

5) Application and the characteristics

The objective of this section is to offer a synopsis of the research concerning the applications and features of MGT [13].

a) Applications

MGT are highly suitable for DG purposes because of their versatility in connection methodologies, their capacity to be clustered together to manage increased loads, their capability to deliver consistent and dependable power, & their lower emissions compared to ICE. The following are some significant applications and functions [13,218,228].

- *Combined heat and power (CHP)*

MGTs are considered as highly compatible with CHP applications owing to their effective recovery of exhaust heat. This recovered thermal energy can either be captured through a heat recovery steam generator or used directly in various applications, enhancing overall system efficiency. MGT-based CHP systems are particularly advantageous in several key markets where consistent thermal and electrical demand exists. In the commercial sector, establishments such as hotels, nursing homes, and health clubs can benefit significantly from the integration of CHP systems, as they require substantial and continuous heating and electricity. Public buildings, including hospitals and government facilities, are also ideal candidates for MGT-based CHP systems due to their round-the-clock operation and energy needs. Furthermore, in the industrial sector, small enterprises, particularly those involved in food processing or manufacturing, often require hot water or low-pressure steam for washing and other processes, making them well-suited for the application of CHP technologies driven by MGTs [13,218,228].

- *Combined cooling heating and power (CCHP)*

Leveraging the exhaust temperature of an MGT can be utilised effectively with absorption cooling systems, which can be powered by either low-pressure steam or the exhaust heat itself. Incorporating cooling into CHP systems is feasible in diverse various commercial and institutional settings to provide both cooling and heating [13,218,228].

- *Resource recovery*

MGT holds significant value for resource recovery purposes, such as utilising digester gas, landfill gas, oil & gas field pumping, power applications, and harnessing CH_4 emissions from coal mines, due to their capability to burn different types of fuels [13,218,228].

- *Load balancing and steady-state power (grid-connected)*.
- *Thermal processing of low-energy fuels or waste gases.*

MGT systems are designed to offer thermal oxidation solutions aimed at eliminating landfills and other waste gases in various applications [13,218,228].

- *High-quality power and enhanced grid stability.*

By leveraging inverter-based generators, CHP systems could seamlessly integrate power quality capabilities into both CHP and standalone power systems. This allows the system to merge with an uninterruptible power supply (UPS), empowering it to initiate autonomously without external power and offering backup power during grid downtime. Additionally, the system could supply support for voltage regulation and address other power quality issues. Such functionalities prove invaluable interruptions, demanding dependable power sources, such as small data centres, hospitals, nursing homes, and other essential service facilities [13,218,228].

- *Power-only applications*

MGT is suitable for providing independent power in remote regions where grid connectivity is unattainable or too expensive. They can also serve as backup power or be used to reduce peak energy demand, although their usage for these purposes is restricted [13,218,228].

- *Microgrids*

MGT, which are generation systems based on inverters, are ideal for use in utility microgrids. They can effectively provide grid support and facilitate grid communication. The companies of Electric power are currently in the process of developing and revealing the application of MGT in this area [13,218,228].

b) Characteristics:

The characteristics section of a micro gas turbine outlines its performance characteristics, technical specifications, and various additional attributes.

- *Performance characteristics*

Table 2-17 provides a concise overview of the cost and performance attributes of CHP systems utilising MGT across many sizes, ranging from 30 kW to 1 MW. The heat rates and efficiencies mentioned depend upon the specifications provided by manufacturers for systems that run on NG, the primary fuel utilised in CHP systems. The table supposes that NG is conveyed at LP, necessitating the use of a booster compressor to elevate the gas pressure before its introduction into the compressed inlet airstream. Both heat and electrical efficiency rates that are provided in the below table are calculated after accounting for power losses from the gas booster compressor. However, the clients who have approached HP gas directly from their native gas utility can keep away from the volume & efficiency losses associated with fuel gas compression. The capital costs that are given in the table are dependent on suppositions of a core grid-connected installation, but the installation expenses may fluctuate depending on different site, regional, and material conditions.

The determination of thermal energy can be derived from turbine data based on the manufacturer's specified exhaust flows and temperatures. The rough thermal recuperation in a CHP system is contingent upon the base of production of space heating and hot water applications. All performance specifications that are given in the table are measured undergoing complete load International Organisation for Standards (ISO) situations, which encompasses a temperature of 59°F, and 60% relative humidity, along a pressure of 14.7 psi. The information in the table indicates that as the size of the MGT increases, its electrical efficiency improves. MGT have lower electrical efficiencies compared to ICE and FC, but they can achieve high overall CHP efficiencies. The relatively higher heat production of MGT, indicated by their low power-to-heat ratios (P/H), highlights the importance of selecting appropriate locations and sizes for these turbines in order to maximise overall efficiency and economic benefits by fully utilising the thermal energy they generate. In the context of managing MGT, it is typically necessary to maintain a fuel supply pressure within the range of 50 to 140 psig. The gas pressures found in local distribution lines can vary, with feeder lines typically ranging from 30-130 psig, and final distribution lines ranging from 1-50 psig. When installing MGT, it is common for sites to opt for HP gas delivery if it is available, as this eliminates the need for a booster compressor and the associated costs, efficiency losses, and capacity limitations. The estimated capital costs for installing MGT can vary depending on the system size, ranging from $4300 per kilowatt (kW) for a 30 kW system to $2500 per kW for a 1000 kW system [218,229].

Table 2-17: Micro-gas turbine cost and performance characteristics [218,229]

MGTs Characteristics	System					
	1	2	3	4	5	6
Nominal Electricity Capacity (kW)	30	65	200	250	333	1000
Compressor Parasitic Power (kW)	2	4	10	10	13	50
Net Electricity Capacity (kW)	28	61	190	240	320	950
Fuel Input (MMBtu/hr, HHV)	0.434	0.876	2.431	3.139	3.894	12.155
Required Fuel Gas Pressure (psig)	55-60	75-80	75-80	80-140	90-140	75-80
Electric Heat rate (Btu/kWh), LHV	13995	12966	11553	11809	10987	11553
Electric Efficiency (%), LHV	24.40%	26.30%	29.50%	28.90%	31.10%	29.50%
Electric Heat rate (Btu/kWh), HHV	15535	14393	12824	13110	12198	12824
Electric Efficiency (%), HHV	21.90%	23.70%	26.60%	26.00%	28.00%	26.60%
CHP Characteristics						
Exhaust Flow (lbs/sec)	0.68	1.13	2.93	4.7	5.3	14.7
Exhaust Temp (^{0}F)	530	592	535	493	512	535
Heat Exchanger Exhaust Temp (^{0}F)	190	190	200	190	190	200
Heat Output (MMBtu/hr)	0.21	0.41	0.88	1.28	1.54	4.43

- *Technical characteristics*

MGT are smaller and less powerful machines that are used for different purposes compared to larger gas turbines. They generally have the following features [217]:

Variable rotation: The rotational velocity of the turbine can vary range from 30,000 to 120000 rpm, contingent upon the specific manufacturer.

High-frequency electric alternator: The generator uses an AC/DC converter and the alternator also serves as the starter of the engine.

Reliability: Several MGT have already accumulated 25,000 hours of operation, which is roughly equivalent to three years, considering shutdowns and maintenance.

Simplicity: The generator is located within the turbine shaft, which simplifies to produce and upkeep. Additionally, it has significant potential for cost-effective mass production.

Compact: Installation & maintenance are straightforward hassle-free.

High noise levels: MGT need a specialised acoustic system in order to decrease noise levels while they are running.

Air-cooled bearings: Utilising air bearings not only safeguards lubricants from contamination by combustion by-products but also extends the equipment while reducing maintenance expenses.

Retrieve: Typically, MGT manufacturers utilise the exhaust gas heat recovery to warm the air entering the combustion chamber, resulting in a thermal efficiency of around 30% [217].

The characteristics of the MGT are outlined in Table 2-18.

Table 2-18: Characteristics of the micro-gas turbines

Characteristic	MGT	Characteristic	MGT
Electric efficiency (HHV)	18-29% [101,230]	Available sizes	30 KW to 350 KW [101]
Overall CHP efficiency	80 - >94 [231,232]	Fuel pressure (psig)	50-140 (compressor) [98]
Effective electrical efficiency	49-57% [98]	Fuels	NG, gasoline, kerosene, diesel, waste and sour gases, distillate fuel oil [101]
Power-to-heat ratio	0.5-0.7 [98]	Uses of thermal output	hot water, chiller, heating [98]
Installation cost ($/KW)	1300-2500 [101]	Power density (KW/m2)	5-70 [98]
Non-fuel O&M costs ($/KWe)	0.009-.013 [98]	Life cycle (year)	4.5-9 [101]
Availability	98-99 [98]	Noise	Moderate [101]
Hours to overhauls	40000-80000 [98]	Part load performance	Satisfied [101]
Start-up time	60 s [98]	Payback period	1.4 years [233]
Size (m^3)	0.63 [98]	NO_x (kg/MWhe)	0.14-0.49 [98]
CO_2 (lb/MWhe)	720 [101]	Output heat temperature	200-315 [101]

6) Current state of the art

Numerous companies from Worldwide are actively working on the development of MGT products. For example, a company called Micro Turbine Technology (MTT) recently introduced the Enertwin system with 3 kW of electrical power, and in that system, NG was used as a fuel. Another company called Bladon also designed an MGT system with 12 kW and in that system diesel or kerosene was used as a fuel. Some MGT have heat recuperator that increases their electrical efficiency. To maximise power generation efficiency and for commercial CHP applications, it is important to achieve the highest possible efficiency. On-going efforts are currently concentrated on enhancing the mechanical design to increase efficiency & reduce equipment expenses. The expense of MGT equipment is approximately $700-$1100 per kilowatt (kW), with an additional installation cost of around $500 per kW. Consequently, the overall cost of MGT is higher compared to ICE [60].

7) List of commercially available MGT

Table 2-19 presents a wide-ranging summary of commercially available micro gas turbines, emphasising their key features, including brand, model, electrical power output, electrical performance, total system efficiency, sound output, and size specifications.

Table 2-19: Micro-gas turbine based micro-CHP systems available in the market [231][234]

Brand	Model	Electrical Output (kW)	Electrical Efficiency (%)	Overall Efficiency (%)	Noise (dB)	Dimensions (mm) (HxWxD)
MTT [231]	Enertwin	3.2	16	> 94	55	995 x 600 x 1170
Capstone [234]	C30	30	26	90	-	1800x760.4x1500

8) Fuel flexibility

Stationary MGT have been specifically created to run on NG as their main source of fuel. On the other hand, MGT intended for transportation purposes usually rely on a liquid fuel like methanol. It is worth mentioning again that MGT have the ability to function using different types of fuels [218].

- **Liquefied petroleum gas (LPG):** Blends comprising propane & butane [218].
- **Sour gas:** Unrefined NG in its raw form as it is extracted from a gas well [218].
- **Biogas:** These gases are derived from the decomposition of organic waste materials, including sewage digester gas, landfill gas, & animal waste digester gas [218].
- **Industrial waste gases:** Emissions from flares and by-products of industrial processes in refineries, chemical plants, etc. [218].
- **Manufactured gases:** Usually, gas with low and medium Btu levels is generated as a result of a process of gasification. Certain substances found in waste fuels, such as acid gas components (such as halogens, hydrogen sulphide (H_2S), anhydrous ammonia (NH_3), salts, and NH_3 compounds, etc.) and oils, can act as contaminants and give rise to concerns. During the process of combustion, halogen and sulphur compounds combine to produce emissions of halogen acids, sulphur trioxide (SO_3), sulphur dioxide (SO_2), & potentially sulphuric acid (H_2SO_4). These acidic emissions have the power to cause corrosion in downstream equipment. To prevent and avoid corrosion and erosion of components, it is crucial to maintain low concentrations of solid particulates. If the

levels of fuel contaminants exceed the specifications set by the manufacturer, various measures such as fuel scrubbing, droplet separation and filtration become necessary. LFG frequently includes chlorine compounds, organic acids, sulphur compounds, & silicon compounds, necessitating fuel pre-treatment. Siloxane compounds pose a specific worry in wastewater treatment & landfill utilisation. They are commonly found in various products & ultimately find their way into landfills & wastewater. When subjected to high temperatures in the combustion and exhaust sections of a turbine, Siloxanes undergo a transformation, forming hard deposits of silicon dioxide, which could eventually result in turbine failure [218].

9) Benefits and limitations

MGT are preferred for household applications as compared to IC engines because of their less emission, small size, lighter weight, lower combustion temperature, etc. They have a quick response time, typically in seconds, making them suitable for backup power. MGT are also easy to maintain with maintenance required for every 5,000-8,000 hours, which is twice as long as the maintenance interval for IC engines. Furthermore, MGT can utilise various fuels such as NG, H_2, hythane, propane, etc. MGT have some drawbacks as well such as low efficiency, high cost, short lifespan (around 10 years), and high operation and maintenance expenses. Additionally, the power output of MGT will decrease at higher elevations and temperatures, which is undesirable in some places and during summer and hot weather [60].

The benefits and limitations of micro-gas turbines are outlined in Table 2-20.

Table 2-20: Advantages and disadvantages of micro-gas turbines [98,101,231,235–238]

Advantages	Disadvantages
Quick start-up (approximately 60 seconds)	Fuel requires high pressure (typically 3–5 bar for MGT)
Lightweight and compact (around 205 kg without water and oil, 215 kg with)	Low electrical efficiency.
Highly reliable with minimal moving parts (only one)	High capital expenditure ($1300–2500 per kW)
Low emissions: NOx (kg/MWhe) = 0.14–0.49 NOx 9-37 ppm @ 15% O_2 CO_2 (kg/MWhe) = 327 CO 40-80 ppm @15% O_2	Requires high-speed bearings and generators, with limitations on continuous on/off cycles

10) Comparisons with internal combustion engines

An alternative to the combined cycle setup, consisting of an MGT and a bottoming ORC for producing electricity is to use a diesel engine instead of the GT. The diesel engine offers the advantage of a quicker response time when starting and higher efficiency. However, it does have some drawbacks when compared to a GT.

- The level of vibration in a diesel engine is more than a GT.
- Without a catalyst, the diesel engine could not match the GT in terms of NOx emissions. The GT emits significantly less NOx, around 40 mg/Nm^3 compared to the diesel engine's 500 mg/Nm^3 at 5% O_2.
- Generally, GTs have lower maintenance costs than diesel engines.
- Normally, diesel engines occupy more space and volume than GTs with the same nominal power.

Even though diesel engines are more efficient, it can be argued that the increase in efficiency achieved by the incorporation of a bottoming ORC with the GT meets the criteria for high-efficiency electricity production, all while still retaining the benefits of the GT [226].

11) Market analysis / Market size

MGT are seen as a viable choice for distributed generation or cogeneration, commonly utilised in commercial settings. However, further advancements are required, such as improved fuel adaptability and increased efficiency. Nevertheless, the main obstacle hindering the micro-CHP market is expected to be non-technical. For instance, if MGT are permitted to supply power to the grid at a fair rate, they could gain widespread acceptance among commercial building owners, including hotels and restaurants. Should 1-kW scale MGT become readily available and offer a lower price point as anticipated, they would emerge as formidable content within the micro-CHP sector when compared to Stirling or Rankine cycle machines [60]. MGTs are currently offered in various sizes, covering a broad range of power outputs [228]. In 2021, the global market for MGTs was valued at approximately US$ 61.85 million, with projections to reach US$ 139.6 million by 2030 [239].

Figure 2-27 illustrates the projected MGT market size for MGTs from 2021 to 2030 in USD millions.

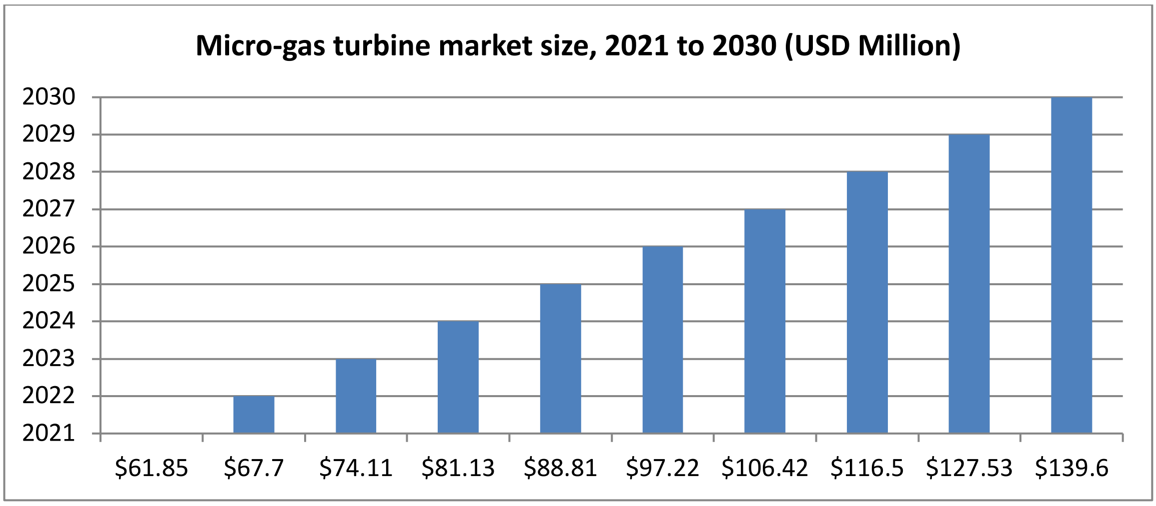

Figure 2-27: Micro-gas turbine market growth from 2021 to 2030 (USD Million), adopted from [239]

12)Future industry and technology trends

The on-going research by MGT focuses on various aspects such as the utilisation of alternative fuels, implementing heat recovery, modifications of design, and integrating FC technology with MGT. These efforts aim to broaden the market for MGT [60,107].

The electric power range of the present MGT is typically 25 kW or higher and which is too large for domestic, and household-based micro-CHP units. For residential use, the ideal prime mover should hover around 1 kW. MTT, headquartered in the Netherlands, has developed a system that generates approximately 4 kW of mechanical power. Their goal is to create a 1 kW MGT-based CHP system with an electrical efficiency of 10-15% [60].

2.3 Feasibility Study of Biomass, Biofuels, and Anaerobic Digestion System,

This section conducted a feasibility study of Biomass, Biofuels, Anaerobic Digestion systems, hythane, and hydrogen, exploring their viability in practical applications. Additionally, this chapter encompassed an analysis of the production processes of different biofuels, such as hythane derived from diverse organic wastes. Furthermore, it outlined the key research and demonstration challenges associated with utilising hythane in a micro-CHP system.

2.3.1 Biomass

Biomass refers to organic material obtained from plants and animals, and it is inherently renewable. This refers to the utilisation of biological matter as a sustainable energy source, commonly generated through agricultural, forestry, or aquaculture practices, for energy production. Biomass serves as an energy resource that stores solar energy in the form of chemical energy. Through photosynthesis, plants create biomass, which can be either by directly burning the biomass for heat or by converting it into renewable liquid and gaseous fuels through a variety of technologies [240,241].

Biomass can come from multiple sources for energy production, such as:

- Wood and by-products from wood processing, such as waste from paper mills, wood chips, firewood, and wood pellets.
- Various crops and by-products including corn, sugar cane, switchgrass, soybeans, woody plants, and more. Processing leftovers are primarily utilised for the production of biofuels.
- Municipal solid waste contains biogenic materials such as paper, wool products, cotton, wood wastes, etc.
- Using animal waste and human sewage to generate biogas or renewable NG [240,242,243].

1) Converting biomass to energy

Various methods are utilised to convert biomass into usable energy, such as.

- Burning can be employed to directly generate the heat.
- Thermochemical conversion has the capability to produce solid, liquid, and gaseous fuels.
- Chemical conversion has the potential to generate liquid fuels.
- Biological conversion demonstrates the capacity to yield both liquid and gaseous fuels [240,244–246].

a) Direct combustion

The predominant method of converting biomass into usable energy involves direct combustion. This involves burning biomass directly to provide heat for buildings and water, industrial process heating, and electricity generation via steam turbines [240,244–246].

b) Thermochemical conversion

The conversion of biomass through thermochemical methods involves pyrolysis & gasification processes. These methods entitle heating biomass materials in enclosed vessels known as gasifiers at high temperatures. The primary distinction between the two lay in the temperature and the involvement of oxygen throughout the conversion method.

- Pyrolysis involves the process of heating organic substances to temperatures ranging from 400 to 500 degrees Celsius in the absence of oxygen. This method of biomass pyrolysis results in the production of various types of fuels, including renewable diesel, charcoal, CH_4, bio-oil, and H_2.
- Hydro treating is a method that involves treating bio-oil, which is produced via rapid pyrolysis, with H_2 under elevated temperatures and pressure alongside a catalyst. This technique is used to create renewable jet fuel, gasoline, and diesel.
- Gasification involves heating organic materials to temperatures ranging from 800 to 900 °C, while injecting controlled quantities of O_2 and/or steam into the container. This process produces a gas called synthesis gas also known as syngas, abundant in CO & H_2. Syngas is applicable as a fuel for diesel engines, for heating purposes, or for electricity generation in GTs. It may also undergo refining processes to isolate H_2, which can then be combusted or employed in fuel cells. Furthermore, syngas can be processed into liquid fuels through the Fischer–Tropsch synthesis [240,244–246].

c) Chemical conversion

Tran's esterification is a chemical process that is utilised to convert greases, vegetable oils, and animal into fatty acid methyl esters (FAME). These FAMEs are then utilised in the production of biodiesel [240,244–246].

d) Biological conversion

Biological conversion encompasses the utilisation of fermentation for biomass conversion into ethanol, as well as anaerobic digestion for renewable NG production. Ethanol is widely employed as a fuel for vehicles. Renewable NG, alternatively referred to as biogas or bio-CH_4, is generated via anaerobic digestion at sewage treatment plants, dairy farms, livestock operations, and landfill sites, biogas can be extracted. When appropriately treated, renewable NG can be used in the same way as fossil fuel NG [240,244–246].

2.3.2 Biofuels

Biomass possesses a distinctive capacity for direct conversion into liquid fuels known as biofuels, meeting transportation fuel requirements, and setting it apart from other renewable energy sources [245,247]. Biofuels are derived from renewable biological sources like algae and plants. They provide a solution to a provocation faced by wind, solar, and other sources of alternative energy. While these sources hold promise in reducing our reliance on fossil fuels and offering environmental and economic advantages, they cannot supplant liquid fuels like jet fuel, gasoline, and diesel fuel, crucial for transportation. This is where biofuels come in, offering a potential solution to this limitation [248]. Biofuels have gained significant attention with the increasing energy resources demand & concerns about GHG emissions. Unlike other renewable energy sources, biofuels offer liquid fuels that are crucial for transportation. They are categorised into four types of generations based on the feedstock type that is used. The initial iteration of biofuels relied on edible biomass; a practice that has generated considerable debate due to its potential to compete with global food demands. In response, second-generation biofuels have emerged, utilising non-edible biomass as a more sustainable alternative. However, challenges persist in terms of cost-effectiveness when attempting to scale up production. Third-generation biofuels have brought about the utilisation of microorganisms as feedstock, while fourth-generation biofuels have sought to enhance these microorganisms through genetic modification. The objective of this modification is to attain a higher hydrogen-to-carbon yield and establish an artificial carbon sink, thereby mitigating carbon emissions. It is important to note that these latter two generations of biofuel industry is still evolving [249]. Figure 2-28 shows the different generations of biofuels.

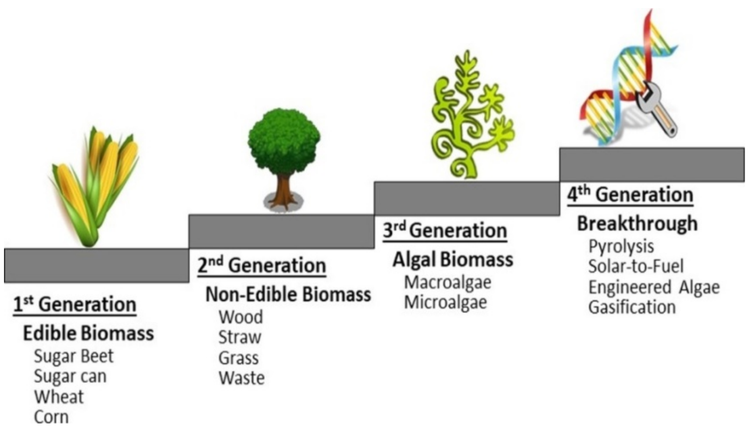

Figure 2-28: Different generations of biofuel [249]

1) Biofuel types

There are different types of biofuel but Ethanol and biodiesel stand as the two most prevalent forms of biofuels currently being utilised, and they are considered the initial generation of biofuel technology [247].

a) Ethanol

Ethanol (CH_3CH_2OH) is a sustainable fuel derived from organic matter, also referred to as biomass, and produced via fermentation. In microbial metabolism, plant sugars are converted into ethanol. Ethanol is frequently employed as a blending component with gasoline to enhance octane levels & minimise emissions. The most utilised blend is E10, comprising 10 percent ethanol and 90 percent gasoline. This blend is authorised for utilisation in many conventional gasoline-powered vehicles. There is also E15, which contains 15% ethanol and 85% gasoline and is also approved for use in certain vehicles. Additionally, there are flexible fuel vehicles capable of running on E85, a blend of ethanol & gasoline with a higher ethanol content ranging from 51% to 83%, depending on location and season. E85 is considered an alternative fuel to regular gasoline [243,247].

Brazil and the United States rank among the top producers of ethanol-based biofuels. In the U.S, ethanol is primarily derived from corn and is typically blended with gasoline to create gasohol; a fuel mixture containing about 10% ethanol. In contrast, Brazil primarily produces ethanol from sugarcane, where it is either used as a standalone fuel (100% ethanol) or blended with gasoline at concentrations as high as 85% [250].

b) Biodiesel

Biodiesel predominantly produced from oil-rich crops such as soybeans and oil palms. To a lesser extent, it can also be derived from alternative oily feedstock's like used cooking oils from restaurant deep-frying operations [250]. Compared to conventional petroleum-based diesel, biodiesel offers a more environmentally sustainable option. It is made by mixing alcohol with animal fat, vegetable oil, etc. Biodiesel is non-toxic, biodegradable, and emits fewer pollutants when burned. Biodiesel, like diesel made from petroleum, is utilised as a fuel for diesel engines. It could be mixed with petroleum diesel in various proportions, such as B100 (pure biodiesel) or the more frequently utilised blend, B20 comprises 20% biodiesel & 80% petroleum diesel [243,247].

The European Union (EU) leads biodiesel producer production, contributing 34% of the global output, which reached 41 million tons in 2018. The term "biodiesel" encompasses various types of biofuels such as fatty acid methyl ester (FAME), hydrogenated vegetable oil (HVO), and biofuels derived from vegetable oils through petroleum refining processes. In Europe, rapeseed oil is the primary feedstock for biodiesel production, while soybean oil is the main source in the Americas. Soybean oil is derived as a secondary product during the production of soybean meal and is used in biodiesel production due to the increasing demand for soybean meal for animal feed. The EU-28, the US, Brazil, and Argentina are the most important biodiesel producers, with the Southeast Asian region gaining importance in the market. Indonesia and Malaysia stand out as major producers of palm oil, are increasing their biodiesel production to stabilise prices and reduce oil imports. Global vegetable oil output has exceeded 200 million tons for the second time in the 2019/2020 marketing year [251].

c) Biogas

Biogas, rich in energy content, is generated through the anaerobic decomposition of biomass or via thermochemical conversion methods such as gasification. It is primarily made up of CH_4, which is the same compound found in NG, as well as CO_2. The CH_4 concentration in unprocessed biogas typically falls within the range of 40-60%, while CO_2 constitutes much of the remaining gas, accompanied by minor quantities of water vapour and assorted gases. Biogas could be utilised as a fuel in its raw form or subjected to purification processes to eliminate CO_2 and other gases, resulting in a product resembling NG. This refined biogas is sometimes referred to as renewable NG or bio- CH_4. Anaerobic decomposition of biomass happens as anaerobic bacteria, capable of serving without oxygen, consume and break down biomass, to produce biogas. These bacteria are indigenous to terrestrial environments such as soil, as well as aquatic habitats including swamps and lakes. Additionally, they are commonly present in the digestive system of both humans and animals. Biogas can be generated and harvested from landfills containing municipal solid waste, as well as from holding ponds used for managing livestock manure. In addition, controlled environments such as anaerobic digesters can be employed to generate this substance. The by-product resulting from the anaerobic digestion procedure is referred to as digestate, possessing a rich nutrient content that could be effectively employed as fertilizer [252]. Biogas could be combusted to generate heat, electricity, or a combination of both. Another option is to refine the biogas into pure CH_4, also known as bio-CH_4, by eliminating other gases. This purified bio-CH_4 can then be utilised as a replacement for NG [253].

2) Biofuels production from organic waste

The section on biofuel production from organic waste discusses various methods of ethanol production, including processes utilising sugarcane, corn, wheat, and sorghum. It also covers the production of biofuels from food waste and highlights the creation of biodiesel from soybeans, vegetable oil crops, oilseed crops, and other sources.

a) Ethanol production from sugarcane

Brazil holds the title of being the largest sugarcane producer globally [254]. Research featured in the Energy Policy journal, suggests that Brazil may need to increase its sugarcane production by over than 5 million hectares by 2030 to meet the growing need for ethanol biofuels. This expansion could potentially impact the country's carbon emissions and deforestation rates. The recent study also predicts that the demand for sugarcane ethanol by 2030 could increase by 17.5 to 34.4 million metric tons. The research indicates that it is possible to fulfil this demand without contributing to further deforestation by implementing enhanced ranching techniques and transforming current cattle pastures in Brazil into sugarcane fields. Brazil has become a global frontrunner in the production of ethanol biofuels, with a strong focus on domestic consumption. In 2018, Brazilian consumers purchased a staggering 33 billion litres of sugarcane ethanol. This increase in biofuel utilisation is largely attributed to a national law mandating a 27 percent ethanol blend in gasoline. Moreover, the majority of vehicles in Brazil are "flex-fuel," meaning they can operate on either mixed fuel or pure ethanol, providing drivers with the freedom to choose [255]. The production of ethanol from sugarcane follows a highly standardised process with minimal variations among plants. These differences primarily stem from the equipment type and calibre, operational controls, and management practices. During the initial phases of the industry in Brazil, the overall efficiency stood at 66 percent. However, with advancements and improvements, the average efficiency has now surpassed 86% [256].

b) Ethanol production from corn /maize

Brazil ranks as the third largest corn producer globally, while the US holds the top position. Corn is a versatile crop that is not only used for food production but also significantly contributes to the production of ethanol, a liquid biofuel. In the US, corn ethanol is commonly mixed with gasoline to create "gasohol," a fuel containing 10 percent ethanol, commonly used in automobiles [257].

c) Ethanol production from corn and wheat

Bioethanol derived from corn and wheat is typically categorised as a first-generation biofuel, contrasting with alternative biofuel sources, due to it focusing solely on fermenting hexose sugar. By employing simpler methods such as grinding, milling, cooking, and liquefaction, high concentrations of ethanol, exceeding 5%, could be obtained from wheat & corn. This is achieved by utilising the yeast strain Saccharomyces cerevisiae during fermentation. To meet the growing demand for bioethanol, industrial-scale production of bioethanol from corn & wheat has been adopted in both developed & developing regions. The production of fuel ethanol is currently a process with high energy efficiency, and on-going research aims to enhance its sustainable economic feasibility [258].

d) Ethanol production from sorghum

Sorghum is a multifunctional crop, used for human consumption, bioenergy production, and as animal feed. There are chances to create various kinds of biofuels using biomass derived from sorghum. Sorghum has a wide range of genetic resources that can be utilised as a bioenergy crop without compromising its value as a crop for food & nutritional security. Bioenergy crops offer a chance for agriculture to contribute to the solution for energy production & climate change mitigation. This review offers an in-depth examination and up-to-date insights into the transformation of sorghum biomass, encompassing stalks, leaves, and grains—into various forms of biofuels. These include liquid biofuels like bioethanol, biodiesel, and bio-oil, gas forms like bio-H_2, biogas, and syngas, as well as solid biochar. The advancement in various pre-treatment & conversion methods for biomass derived from sorghum, including thermochemical, biochemical, chemical, & biological processes, is emphasised and explained. Additionally, the review summarises the various value-added products derived from sorghum that are becoming increasingly important in biofuel production. The potential prospects for sorghum-based bio refineries and opportunities for enhancing the production of biofuels derived from sorghum are presented and discussed. The concept of a bio refinery presents significant potential in optimising the use of sorghum biomass for biofuel and biochemical production. However, further research is required to determine the most efficient methods for pre-treatment, processing, and product generation from different biomass sources. Given its high biomass generation and versatile uses, sorghum holds the potential to become a pivotal biofuel crop. Additional investigation is essential to determine the prevalent effective and economical methods for optimising the value of biofuels & other bio products made from sorghum. It is important to conduct a thorough analysis of the entire lifecycle to identify areas for improvement, benefits, and ways to overcome obstacles at various stages. It will be essential to foster strong collaboration between researchers from both governmental and corporate sectors, along with multidisciplinary teams, in order to develop detailed models for bio refineries [259].

e) Biofuel production from waste food

Roughly one-third of the food generated worldwide for human consumption is lost or wasted throughout the supply chain. At present, this wasted food is either disposed of in landfills or burned. However, this waste presents a considerable opportunity to be repurposed as a valuable resource for biofuel production through fermentation methods. This is because food waste contains valuable organic and nutrient-rich components. The management and characteristics of food waste have been extensively studied and converting it into biofuels is seen as a promising strategy. In addition to managing food waste, this approach could also diminish reliance on crude oil, potentially stabilising food prices and addressing society's attitudes towards food waste. This part of the study offers an overview of the present status of food waste, its characteristics, management practices, and innovative uses as a feedstock for biofuel production. The focus is on fermentation technologies that can convert food waste into different forms of biofuels, such as biodiesel, ethanol, H_2, & CH_4 [260].

f) Biodiesel production from soybeans, vegetable oils crops, oilseed crops etc.

Brazil has established itself as a prominent player in the worldwide biodiesel market, ranking fourth in terms of production volume. The country's federal program for biodiesel production is designed to encourage participation from both small-scale family farmers and large agribusiness enterprises, with the objective of cultivating vegetable oil crops specifically for the generation of biodiesel. Presently Brazil holds the position of the second-biggest soybean producer, which serves as the primary raw material for biodiesel manufacturing. However, considering the rising demand for biodiesel & the relatively modest oil productivity of soybeans, Brazil is actively exploring alternative oilseed crops that could be utilised for biodiesel production. This detailed review examines the status of biodiesel production in Brazil and investigates various vegetable oil crops under consideration as potential sources of feedstock's. It is worth noting that Brazil's biodiesel industry is currently functioning at a mere 47% of its total capacity, indicating that there is room for further growth. With its significant bioethanol & biodiesel industries, Brazil is already recognised as a major player in sustainable biofuel production, positioning itself as a pivotal player in the burgeoning bio-based economy [261].

On a global scale, soybeans are the dominant source of feedstock for biodiesel, followed by canola and palm oil, which has experienced a rise in consumption in recent times. However, Brazil's scenario varies, with soybean being the top raw material, followed by bovine fat. Additional sources like cottonseed, frying oil, and palm oil occupy the remaining positions. Soybean serves as the primary oil source utilised in Brazilian biodiesel production [256].

2.3.3 Anaerobic digestion / Bio digestion system

Anaerobic digestion, also known as bio digestion, is a natural process where microorganisms decompose organic materials. In this case, "organic" refers to materials derived from plants or animals. Anaerobic digestion occurs in enclosed environments without oxygen. The term "AD" can refer to either the process itself or the system, called a digester, in which anaerobic digestion occurs. The materials listed below are typically classified as "organic" and can be treated in a digester:

- Manure from animals
- Leftover food
- Oils and fats
- Organic waste from industries
- Treated sewage waste (biosolids)

All anaerobic digestion systems follow the same fundamental principles, regardless of whether they are used for food waste, wastewater sludge, animal manures, etc. While there may be variations in design, the overall process remains unchanged. Biogas is produced via anaerobic digestion, during which microorganisms decompose organic materials without the presence of oxygen. The resulting biogas primarily CH_4 and CO_2, alongside a minor quantity of H_2O vapour and other gases. By removing the CO_2 and other gases, the biogas can be purified to contain only CH_4. CH_4 is the main component of NG. The residue left after anaerobic digestion is referred to as "digestate," a moist mixture typically separated into solid and liquid components. Digestate is a highly nutritious substance that can be effectively employed as a fertilizer for agricultural purposes. Biogas is generated during the anaerobic digestion process and serves as a sustainable energy resource with diverse applications. Biogas finds application in communities and businesses nationwide [262,263].

- Engines that generate power create mechanical energy, heat, and/or electricity (including systems that generate both heat and power).
- Boilers and furnaces that use fuel to heat digesters and other areas.
- Operate vehicles that run on alternative fuels.
- Provide NG to homes and businesses through the pipeline

The usage and efficiency of biogas depend on its quality. Biogas is commonly purified to eliminate CO_2, water vapour, and other impurities, which enhances its energy value. Biogas of lower quality is typically utilised in less efficient engines like internal combustion engines. On the other hand, higher-quality biogas that has been purified could be utilised in engines that are both more efficient and more intricate. Biogas that satisfies the criteria for pipeline quality could be effectively transported through existing natural gas pipelines and utilised in both residential & commercial environments. Furthermore, biogas can undergo purification and enhancement processes to generate compressed natural gas (CNG) or liquefied natural gas (LNG), which can serve as viable fuel alternatives for automobiles and trucks [262]. Figure 2-29 shows the anaerobic digestion process.

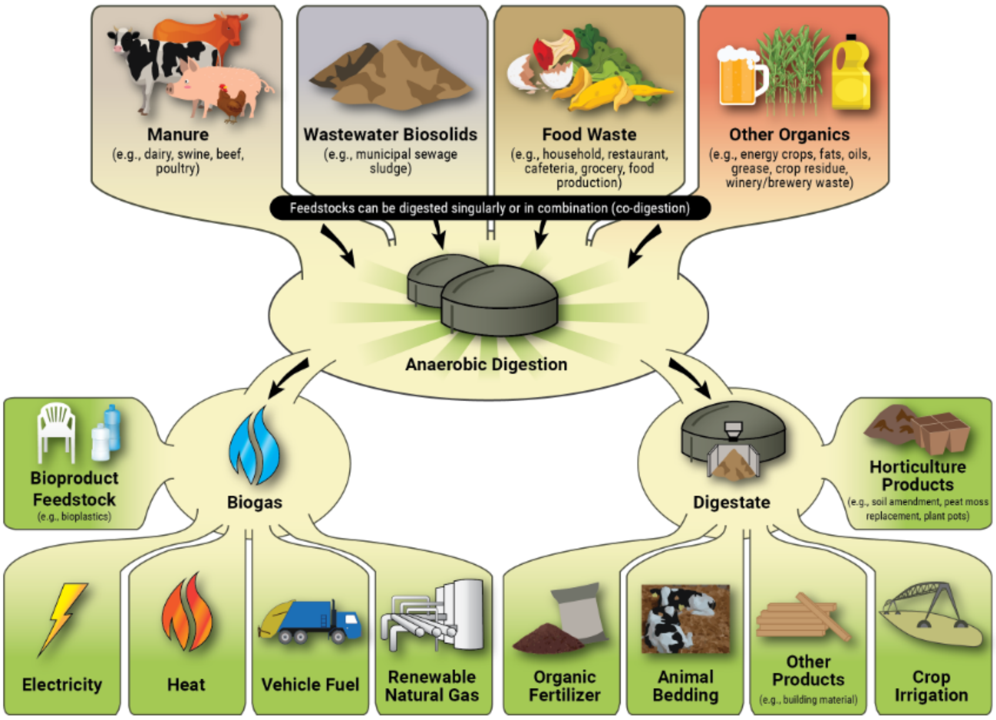

Figure 2-29: Anaerobic digester process [264]

The process of anaerobic digestion consists of four main stages, which are given below.

1) Hydrolysis

Biomass generally comprises substantial organic polymers. For bacteria within anaerobic digesters to effectively harness the energy contained in this material, it is imperative that the polymers comprising the material undergo degradation into smaller constituents. These smaller components, known as monomers, such as sugars, can then be easily accessed by other bacteria. The phenomenon of decomposing polymers and solubilising the resultant smaller molecules into a liquid medium is commonly known as hydrolysis [263,265,266].

2) Acidogenesis

The process of acidogenesis involves the breakdown of remaining components by acidogenic bacteria, leading to the formation of volatile fatty acids (VFAs), ammonia, CO_2, H_2 sulphide, & additional by-products. This process is comparable to the souring of milk [263,265,266].

3) Acetogenesis

The acetogenesis phase represents the third stage of anaerobic digestion. In the following stage, acetogenesis, acidogenic bacteria further process these simpler molecules—mainly producing acetic acid, along with CO_2 and H_2 [263,265,266].

4) Methanogenesis

The ultimate stage of anaerobic digestion is known as methanogenesis, which occurs through a biological process. During this stage, methanogens utilise the by-products from earlier stages and transform them into CH_4, CO_2, and H_2O. These substances form the main components of the biogas released by the system. Methanogenesis is influenced by pH levels, with the optimal range being between 6.5 and 8 for efficient methane production. Any organic matter that remains undegraded, along with dead microbial cells, constitutes the digestate. [263,265,266].

2.4 Key research and demonstration challenges of a hythane and hydrogen burnt micro-CHP system

The following are the main research and demonstration challenges associated with a hythane and hydrogen-fuelled micro-CHP system.

2.4.1 Hythane / Biohythane

Bio-CH_4 is a commonly known form of biogas, while bio-H_2 has been recognised for approximately twenty years. On the other hand, hythane has only gained recognition in recent years. Bio-H_2 is produced through the biological fermentation process and is recognised for its potential as a future fuel source. It is considered attractive and feasible for use in an H_2-based economy. Various organic materials, such as organic waste, wastewater, and algal biomass, can serve as raw materials for bio-H_2 generation via fermentation. Progress in research and technology developments in this area has shown promising advancements, positioning bio-H_2 as a promising biofuel technology [267].

Hythane, also known as Biohythane, is a blended fuel composed of H_2 and CH_4. It is created through a two-stage anaerobic fermentation (TSAF) process, which integrates the generation of bio hydrogen and bio methane. This approach is deemed a viable method for producing eco-friendly hythane from waste biomass. Hythane offers several advantages compared to traditional biogas, including enhanced environmental friendliness, greater energy retrieval, and reduced fermentation duration. Nevertheless, most of the on-going initiatives aimed at transforming waste biomass into hythane are still in the initial and experimental phases. Therefore, it is crucial to conduct further studies and scale up the system for industrial application. In the hythane process, H_2 serves as an intermediate product quickly consumed by CH_4-producing bacteria. Nevertheless, during this process, it is possible to separate the two stages or decouple the production of H_2 and CH_4. Additionally, hythane offers several other benefits.

- The combustion of CH_4 in an engine is sped up by adding H_2.
- Mixing H_2 with CH_4 improves its ability to ignite in lean conditions.
- H_2 has a flame speed that is eight times faster than CH_4 when the air/fuel mixture is in a lean condition.

The production of H_2 and CH_4 through biological means has great potential as a future fuel source. This can be achieved by utilising different types of waste. The utilisation of waste to produce hythane offers a twofold advantage, as it enhances both energy recovery from the waste and the remediation of the waste itself. In conventional dark fermentation (DF) processes, the maximum potential energy recovery is limited to a mere 30% according to theoretical calculations. However, a significant amount of spent material is generated after DF, which contains valuable components like volatile fatty acids & ethanol. By simply increasing the pH, this residual material could be directly utilised for CH_4 production, resulting in an overall increase in energy recovery from a specific substrate [268,269]. Figure 2-30 shows the complete production process of hythane via TSAF.

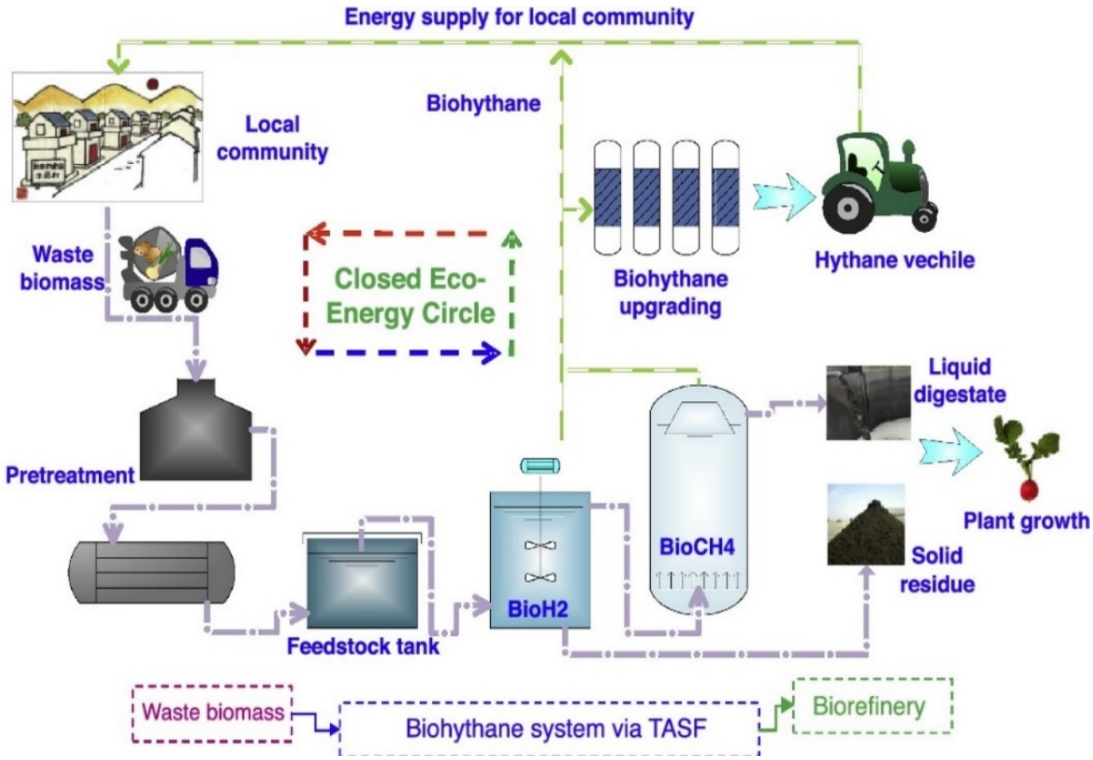

Figure 2-30: Hythane production process by combining hydrogen and methane together via TSAF [270]

Hythane has not been fully evaluated, so there is still more work and research required to address technical, & economic aspects, and associated issues with using hythane as a viable renewable fuel. According to Schievano et al., bio-H_2 and bio-CH_4 can be concurrently generated via a two-stage anaerobic digestion process, potentially enhancing energy recovery by 8-43%. This could make anaerobic techniques more cost-effective, as suggested by Arimi et al. On the other hand, combining bio-H_2 and bio-CH_4 to create hythane can potentially improve efficiency in the combustion process [267].

1) Two-stage hythane production process

Generation of hythane through a TSAF process is advantageous due to its relatively short fermentation duration ranging from 13-18 days, and the involvement of two separate microbial communities. During the initial phase, acidogenic bacteria like Enterobacter sp., Caldicellulosiruptor sp., Thermotoga sp., Clostridium sp., and Thermoanaero bacterium sp. are primarily responsible for the fermentation process. Likewise, during the second stage, prominent methanogenic archaea, specifically

Methanosarcina sp. and Methanoculleus sp., become prevalent when the acetate concentration exceeds 1.2 mm. The primary objective of this TSAF process is to effectively harness energy recovery, with an approximate energy recovery rate of 67.70%, from the degradative organic components present in biomass. This process involves the continuous integration of bio-H_2 with bio-CH_4, resulting in the production of hythane using certain commercially available two-stage techniques, as shown in Figure 2-31 [267,271].

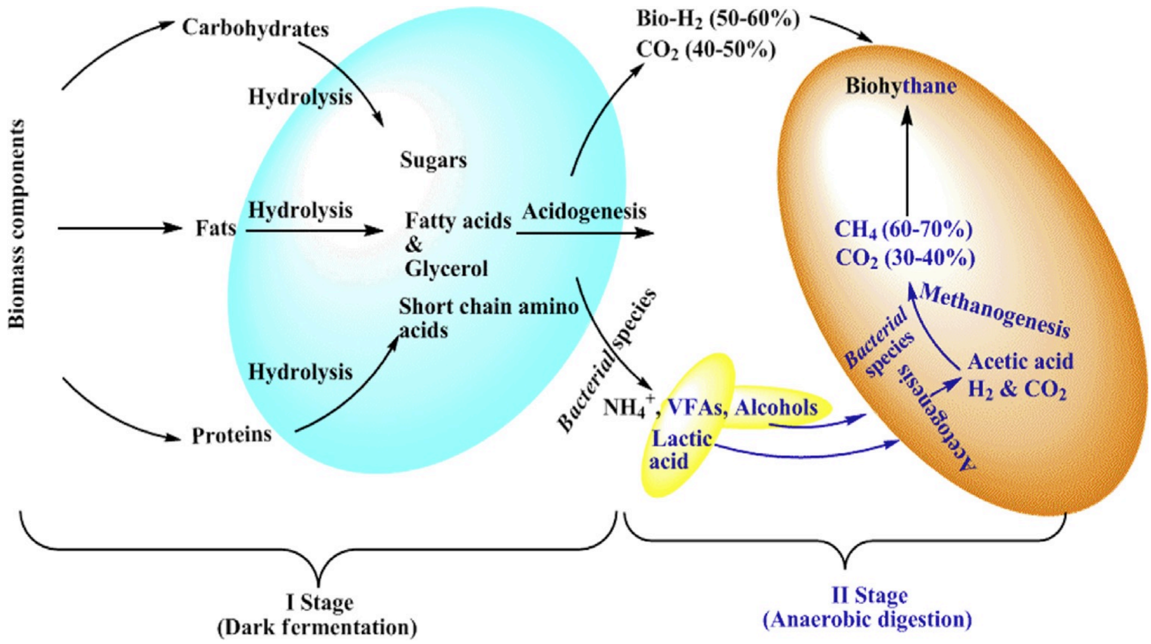

Figure 2-31: TSAF process for the production of hythane [267]

2) One-stage hythane production process

Furthermore, aside from the utilisation of TSAF methods to produce hythane, scholars have also investigated the feasibility of generating hythane through one-stage methodologies. While it may seem that two-stage processes are more efficient in terms of bio-kinetic performance, one-stage processes have demonstrated fascinating microbial dynamics and functional interactions during hythane production. In one-stage process, the production of H_2 setup significantly impacts the reaction rate and ultimately governs the composition of hythane. This procedure involves the generation of VFAs through acidogens, which are then consumed by methanogens, resulting in the simultaneous generation of both H_2 and CH_4. The balance between VFA production and consumption is critical, as it directly affects the coordinated activity of acidogens and methanogens required for synchronised H_2 and CH_4 generation in a single-stage bioreactor system [267].

3) Difference between dark fermentation & anaerobic digestion

Both anaerobic digestion (AD) & dark fermentation (DF) are types of anaerobic fermentations. DF comprises the initial two stages of AD, namely hydrolysis and acidogenesis. The goal of DF is to produce H_2, while AD has the objective of generating biogas that can be subsequently enhanced to bio-CH_4. The primary distinction between the two processes lies in their operating conditions.

To control the growth of methanogens, which are responsible for consuming H_2 in the process of DF, various strategies can be employed. These strategies include pre-treating the inoculum, operating the system with a low hydraulic retention time (HRT), and maintaining a pH level below 7. On the other hand, AD typically operates with a high HRT and a pH close to 7. To optimise energy generation and eliminate chemical oxygen demand (COD), the process of AD is frequently employed subsequent to the application of dissolved air flotation (DF). These reviews may provide useful information on the subject [272–275]. Figure 2-32 shows the modification of AD for hythane production from organic wastes via the TSAF process.

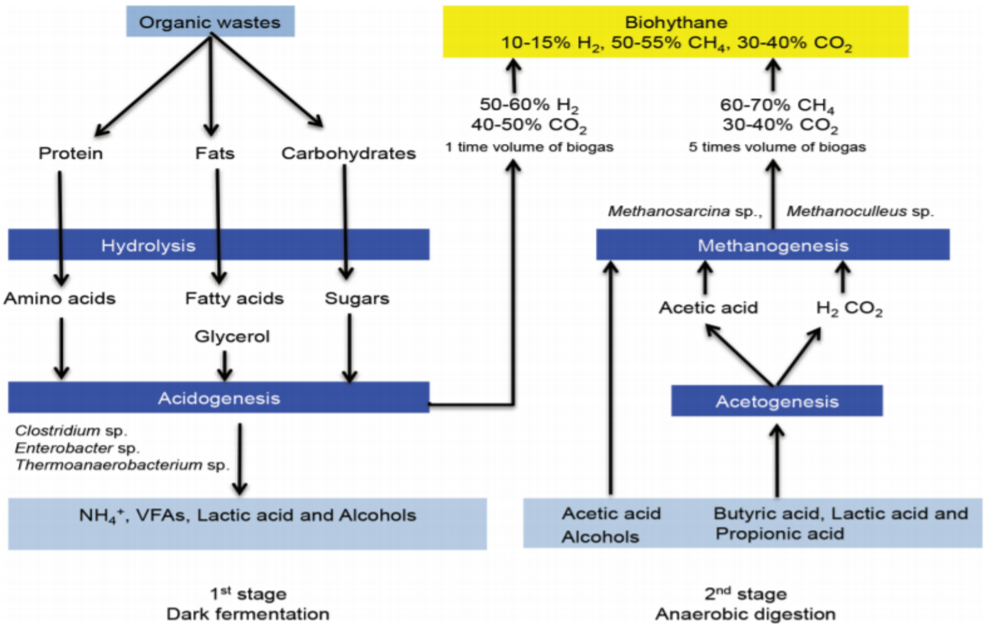

Figure 2-32: Changes in anaerobic digestion for hythane production from organic wastes utilising TSAF process [276]

4) Hythane production from organic waste

The section on hythane production from organic waste explores different methods for producing hythane using food processing wastes and various agricultural residues. It examines the processes involved in converting these organic materials into hythane, highlighting the potential benefits and applications of this fuel.

a) *Hythane production from food processing wastes*

The food sector contributes a significant volume of food waste, whether directly or indirectly through food processing activities. This waste can be repurposed to create biofuels as a means of managing waste. The passage discusses six categories of food processing waste: oil, fruit & vegetable, livestock, brewery, dairy, & agriculture-based materials. These waste types can be managed using methods like dark fermentation or anaerobic digestion. However, the existence of polyphenols & essential oils in oil, fruit, & vegetable waste poses challenges to producing H_2 and CH_4. Moreover, dairy, brewery, & livestock waste streams are characterised by high acidity and protein content, which can result in elevated NH_3 levels and the build-up of volatile fatty acids. The text also underscores approaches such as pre-treatment and co-digestion, as well as factors related to operations and the environment that can influence the generation of hythane. Lastly, the paragraph emphasises the significance of feedstock in realising a successful circular economy [277].

b) *Hythane production from various agricultural residues*

The aim of this study was to assess the potential of various agricultural residues for generating hythane through AD, without any prior treatment. The researchers conducted a Biochemical Methane Potential (BMP) analysis on a range of materials, including mixed fruit waste, rice husk (RH), sugarcane bagasse (SW), mixed vegetable waste, and wheat straw. Gas composition was examined using gas chromatography coupled with a thermal conductivity detector (GC-TCD). Results from BMP test indicated that sugarcane bagasse, mixed fruit waste, and mixed vegetable waste (MVW) exhibited an average hythane production percentage of 53.64%, 43.54%, and 40.92%, respectively. In contrast, rice husk & wheat straw yielded percentages of 16.74 percent and 29.75 percent, respectively. The study further observed that agricultural biomass like wheat straw and rice husk produced lower hythane percentages, primarily due to the presence of lignocellulose materials. The primary significance of this research lies in emphasising the potential of hythane production from agricultural residues compared to the production of CH_4 and bio-H_2 [278].

5) Key research and demonstration challenges of a hythane burnt micro-CHP system

This section outlines the key research and practical challenges associated with micro-CHP systems fuelled by hythane combustion.

a) Key research

- Hythane is a globally accessible application available for instant use.
- Small-scale Hythane production units incur relatively low capital investment.
- Hythane is characterised by minimal capital and operational expenditures.
- The production of Hythane has recently attracted public attention, being seen as a promising technology due to its low emissions, cost-effectiveness, environmental benefits, superior energy conversion, higher energy recovery, and decreased fermentation duration.
- Notably, H_2 complements the weaknesses of CH_4. The addition of H_2 can broaden the flammability limits of CH_4, enhancing fuel efficiency. Moreover, H_2 increases the flame speed of CH_4, thus reducing combustion time and improving heat efficiency. Additionally, adding H_2 reduces the quenching distance of CH_4, making ignition easier with lower energy input.
- Compared to compressed NG, the use of Hythane improves fuel efficiency.
- Hythane offers several advantages over conventional biogas, including higher energy efficiency, shorter fermentation periods, adjustable H_2/CH_4 ratios, and a more robust process for handling waste biomass.
- The EU's Naturally project investigated the tolerance levels of the NG grid for H_2 integration. Levinsky et al. found that the safe amount of H_2 that can be mixed with NG depends on NG composition. Generally, a maximum of 20% H_2 by volume is considered safe due to combustion limitations in appliances.
- Using blended fuel instead of pure CH_4 for combustion leads to higher NOx emissions, but increasing the H_2 content in the blend does not substantially alter NOx levels. Conversely, CO emissions show a more noticeable reduction when the H_2 percentage is lower.
- Adding H_2 to CH_4 increases the H/C ratio, resulting in lower greenhouse gas emissions.
- Hythane presents significant advantages over compressed NG, including lower GHG emissions.
- Hythane is more environmentally friendly compared to conventional biogas. [270,276,279–282].

b) Challenges

- Mixing more than 20% H_2 with CH_4 would necessitate replacing almost all of the existing pipelines within residential and commercial buildings.

- At present, producing hythane solely through TSAF is neither economically nor ecologically sustainable. To make TSAF a viable option, it's essential to use waste biomass or wastewater as feedstock, which would significantly lower the feedstock costs.
- The research on hythane remains limited, indicating a need for further studies to determine the exact costs associated with its use.
- Identifying the optimal H_2-to-CH_4 ratio is a significant challenge when using hythane as an engine fuel. At high engine loads, power output slightly decreases, and brake-specific fuel consumption increases. It is also critical to address the storage and supply infrastructure for hythane to prevent potential issues.
- The primary technical challenges include scaling up the hythane production process, improving the performance of bio-H_2 reactors, improved energy efficiency of the hythane system, and refinement of the TSAF process design.
- Additional modifications to combustor designs when using hythane, such as altering fuel injection systems and cooling methods, are necessary to boost engine combustion efficiency.
- Only up to 5-20% H_2 can be blended with CH_4.
- H_2 production is still constrained due to cost and operational limitations.
- In the dark fermentation process, only 7.5%-15% H_2 can be produced.
- Blending 20% H_2 with CH_4 would increase the cost of hythane, as renewable H_2 is typically 6-14 times more expensive than fossil-based gas [270,281–284].

2.4.2 Hydrogen

This section provides an in-depth discussion of hydrogen, covering various aspects such as hydrogen generation technologies, its application as a fuel in gas turbine systems, and the unique properties and combustion challenges associated with hydrogen. It also explores the different utilisations of hydrogen fuel, emphasising its potential role as an energy storage solution. Finally, the section concludes with remarks summarising the key findings and implications for the future of hydrogen in energy systems, highlighting its significance in transitioning towards more sustainable energy solutions.

1) Hydrogen Generation Technologies

As of today, hydrogen is seen as one of the most promising alternatives to fossil fuels. Producing hydrogen fuel however requires a high energy input and there exist several different types of hydrogen:

- Brown Hydrogen is created through coal gasification.
- Grey Hydrogen is synthesised from natural gases and fossil fuels through steam reforming.
- Blue Hydrogen is very similar to the production of grey hydrogen, but the CO_2 emission generated from the steam are captured using carbon capture and storage (CSS) technologies.
- Green Hydrogen is manufactured from electricity which was generated from renewable sources. It is known to be 100% carbon emission free [285].

The Figure 2-33 provides the various classifications of hydrogen.

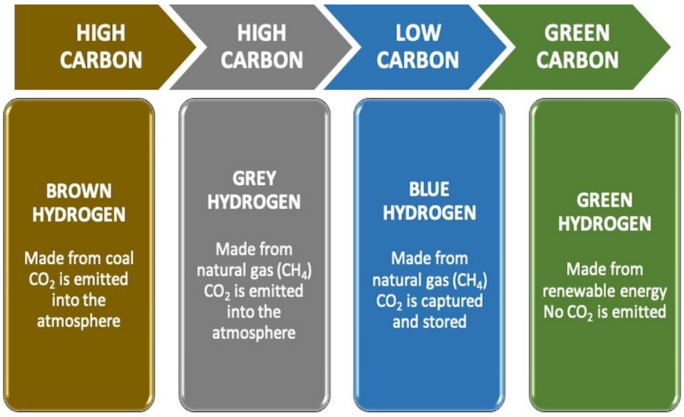

Figure 2-33: Different types of hydrogen [286]

2) Hydrogen Fuel in Gas Turbine Systems

- The International Energy Agency (IEA), in its *Future of Hydrogen report*, emphasises hydrogen's critical role in enabling a global shift toward cleaner energy systems. The report particularly emphasises hydrogen's potential within the power sector, where it can serve as a key fuel for low-carbon electricity generation. As the global energy landscape shifts towards sustainability, hydrogen is expected to complement other renewable energy sources, such as wind and solar, by providing a stable and dispatch able power supply [287].
- Hydrogen gas turbines are increasingly regarded as key technologies in the pursuit of long-term emissions reductions. These systems enhance grid stability by offering flexibility and serving as backup power when variable renewables like solar and wind fall short in electricity generation. Their ability

to operate on hydrogen or hydrogen-blended fuels helps reduce carbon emissions compared to conventional natural gas turbines, aligning with global decarbonisation goals [288].

- On-going advancements in hydrogen combustion technology have led to significant improvements in gas turbine capabilities. For instance, gas turbines currently being tested at the newly established Zero Emission Hydrogen Turbine Centre are designed to operate with up to 75% hydrogen in the fuel mix. This marks a substantial step forward in the transition toward fully hydrogen-powered turbines, supporting the broader goal of minimising dependence on fossil fuels [288].
- The European Turbine Network (ETN), in its most recent report, highlights the strong commitment of the gas turbine industry to achieving 100% hydrogen-powered turbines by 2030. This initiative reflects the industry's dedication to innovation and clean energy, aiming to phase out carbon-based fuels and develop hydrogen-compatible combustion technologies. If successful, this transition will play a crucial role in meeting Europe's ambitious climate targets and promoting widespread hydrogen adoption [288].
- Small-scale gas turbines are also making progress in hydrogen adoption. For example, experimental tests conducted on 3 kWe micro gas turbines have successfully demonstrated operation with fuel mixtures containing 25% hydrogen and methane. This achievement indicates the feasibility of hydrogen utilisation in decentralised power generation systems, including micro-CHP applications, which can provide cleaner energy solutions for residential and small-scale industrial sectors [228].

The Figure 2-34 shows the hydrogen gas turbine.

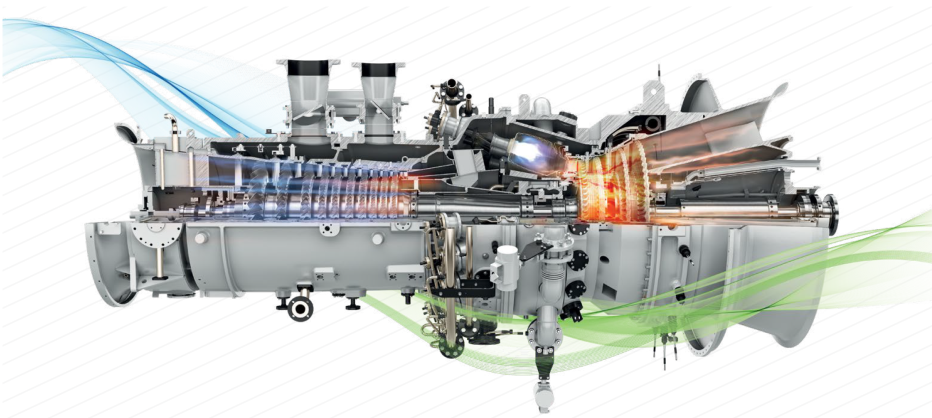

Figure 2-34: Hydrogen gas turbines [288]

3) Hydrogen Properties and Combustion Challenges

- Variation in fluid composition affects the turbine's performance by altering the enthalpy decrease over the turbine stage combined with changes in inlet volumetric flow, which can impact efficiency and power output.
- Compressor-turbine matching becomes more complex as changes in fuel properties affect mass flow rates, pressure ratios, and aerodynamic performance, while blade cooling challenges arise due to variations in combustion temperatures.
- Higher risk of auto ignition is associated with fuels that have a shorter ignition delay time, potentially leading to premature combustion in the combustion chamber or even within the fuel supply system.
- Increased risk of flashback occurs because hydrogen-rich fuels and certain alternative gases have faster flame speeds or shorter ignition delays, increasing the likelihood of flames propagating upstream into the premixing section.
- Modified thermo-acoustic behaviour, including changes in amplitude levels and frequencies, can lead to combustion instability, affecting turbine operation and potentially causing mechanical damage.
- Elevated NOx emissions result from higher combustion temperatures, particularly when burning hydrogen-rich fuels, necessitating advanced emission control strategies.
- Increased pressure drop across the fuel system occurs when using fuels with a lower Wobbe Index, impacting overall efficiency and potentially requiring modifications to fuel injectors and piping.
- Reduced component lifetime arises due to higher heat transfer rates in hot gas path components, leading to accelerated material degradation and an increased need for effective cooling mechanisms to maintain turbine durability [289].

4) Hydrogen Fuel Utilisations

- The Aurelia® A400 turbine is designed to operate on hydrogen, biogas, synthetic gas, and various other renewable or unconventional fuels. These 400 kWe turbines could achieve up to 20% greater energy efficiency [290].

- The upcoming turbines, expected to be delivered shortly, will be designed to utilise hydrogen as a primary fuel, in response to the increasing production of renewable energy [287].
- In 2018, Tanimura's team engineered a turbine that operates a blend of 30% hydrogen and 70% natural gas, a significant step toward a carbon-neutral future. This hybrid-fuel turbine produces approximately 10% less energy [291].
- Mitsubishi Power plans to install its gas turbines at the Intermountain Power Plant by 2025, with a transition to 100% hydrogen power by 2045, supplying electricity to Los Angeles [292].
- HyDeploy is a pioneering demonstration project focused on blending up to 20% hydrogen into the natural gas supply, helping to reduce carbon dioxide (CO_2) emissions. A live demonstration took place on part of the Keel gas network, concluding in March 2021 [293].
- Hydrogen is also well-suited for use in fuel cells, which convert chemical energy directly into electricity through high-efficiency electrochemical processes [294].

5) Hydrogen as an Energy Storage Solution

- Hydrogen is increasingly recognised as a viable medium for storing excess renewable energy, helping to stabilise the grid by matching energy supply with demand [295].
- This process involves using surplus energy from renewable sources such as wind and solar to power electrolysis, which splits water into hydrogen and oxygen. The hydrogen produced can be stored and later reconverted into energy when needed for power generation [296].
- This approach helps address the energy storage challenge by providing a long-term, scalable solution for storing renewable energy, reducing reliance on fossil fuels, and enhancing energy security [295].
- Since solar and wind power are highly variable, their generation does not always match real-time energy demand. Excess electricity can be converted into hydrogen, allowing for efficient energy storage that can be utilised when needed, thereby enhancing grid stability and advancing the shift toward a low-carbon energy infrastructure [295].

The Figure 2-35 presents a sustainable energy system.

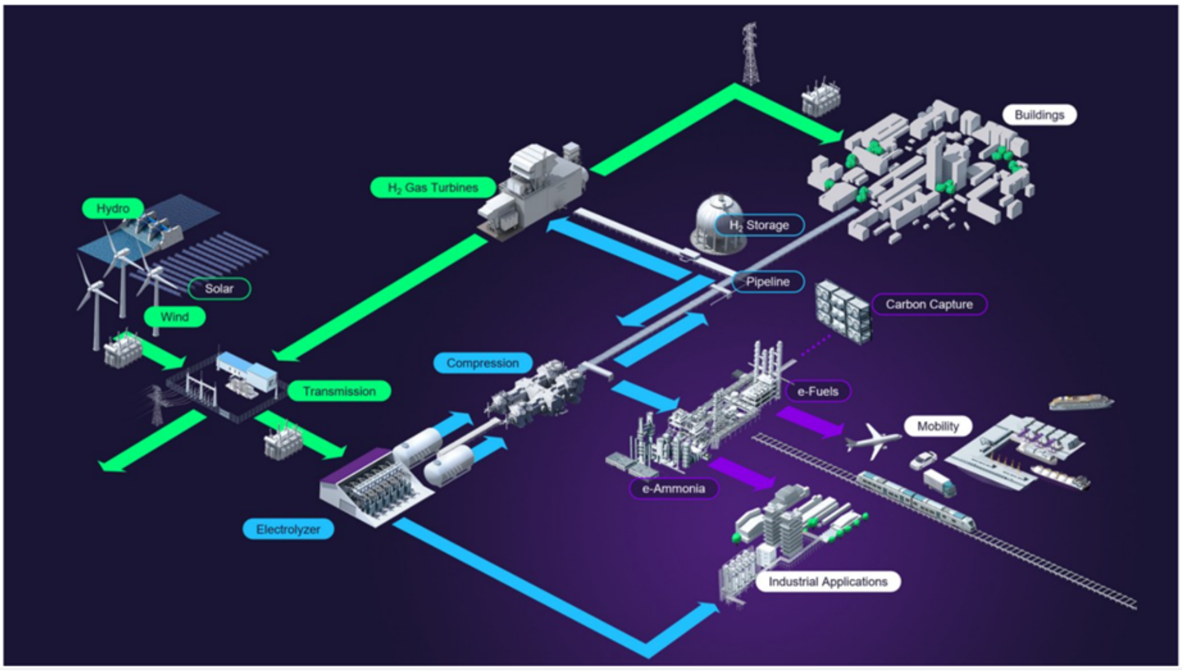

Figure 2-35: A sustainable energy system [295]

6) Concluding remarks

- Hydrogen is increasingly viewed as a critical component in the global transition to clean energy, especially within the power sector.
- Progress in hydrogen production, storage, and its integration into fuel cells and gas turbines present a viable path toward carbon-neutral solutions.
- Currently, hydrogen is widely regarded as the leading alternative to conventional fossil fuels. Producing hydrogen fuel however requires a high energy input, which is why there exist several different types of hydrogen.

3. CHAPTER 3: METHODOLOGY AND EXPERIMENTAL APPROACH

Chapter 3 introduces and provides detailed methodologies for the two software tools used in this project: Aspen Plus, process simulation software, and GasTurb 14, performance analysis software. This chapter outlines the core functions and applications of both software platforms, focusing on their roles in analysing and optimising micro-CHP systems.

The chapter begins with an introduction to Aspen Plus, followed by a detailed explanation of its methodologies for micro-CHP system analysis. The first step covered is system definition and process flow diagram creation, where the components of the micro-CHP system are modelled and their interconnections are represented visually. Next, the chapter discusses the selection of thermodynamic models, which are crucial for simulating energy generation and conversion processes accurately. This is followed by an explanation of defining input data and operating conditions, such as fuel type, system pressures, and temperatures, which are necessary for the simulation. The chapter continues by describing the simulation and performance analysis process, where Aspen Plus is used to evaluate system behaviour under various conditions. Additionally, sensitivity analysis and optimisation are explored, highlighting how key parameters can be varied to maximise system efficiency. The integration of biofuels and renewable energy sources into the simulation is also discussed, demonstrating Aspen Plus's capability to model sustainable energy systems. Finally, the chapter addresses model validation and performance benchmarking, confirming the validity and dependability of the simulation findings.

Similarly, the chapter introduces GasTurb 14 and proceeds to explain its detailed methodology for micro-CHP system analysis. The first section covers system configuration and model development in GasTurb 14, explaining how the software is set up to simulate the components and performance of the micro-CHP system. The thermodynamic modelling and cycle analysis section follows, providing insights into how GasTurb 14 models the energy cycles involved in micro-CHP operation. Off-design performance assessment is discussed next, explaining how the software evaluates system performance under varying loads and conditions outside of the design point. The chapter also explores heat recovery and CHP system integration, showing how GasTurb 14 can model the capture and use of waste heat in the system. Additionally, fuel analysis and emission assessment are covered, emphasising the environmental impact of various fuels on the system's operation. The chapter concludes with a discussion on validation and benchmarking, ensuring that the simulation results are accurate and aligned with real-world data.

3.1 Aspen Plus

Process simulation software plays a crucial role in the power plant design process, facilitating various stages such as design, research, development, and production. It allows for the evaluation of different design configurations under diverse operating conditions without the need for physical experiments. By utilising process modelling, expensive laboratory work can be minimised, thereby supporting research and development initiatives. Additionally, such software aids in the design phase by optimising component sizing for power cycles and enables parameter sensitivity analysis during production without associated risks [297]. In recent years, several process simulation software tools have emerged, including AspenOne, BOAST, Thermoflex, ChemCad, Eclipse, and ProSimplus [222].

Aspen Plus, in particular, is widely recognised for its user-friendly interface and adaptability in supporting various phases of power plant development, from research and development to the operation of fully functional power plants. Originally developed in the 1980s by researchers at MIT and later commercialised by AspenTech, Aspen Plus has evolved into a robust tool for simulating a broad range of processes [298]. Users can create customised process models by first constructing a flow sheet and then specifying chemical components and operational parameters. With a single command, Aspen Plus executes the necessary calculations to predict system performance, providing detailed results that illustrate changes in chemical species across different streams and units within the model [299].

Aspen Plus is a powerful modelling tool capable of simulating and analysing power cycles and chemical processes. It features an extensive database of working fluids and allows users to select various equations of state (EOS) for thermodynamic property calculations. The Peng-Robinson EOS is a fundamental model available for simulating gas turbine cycles, while more advanced EOS options are available for modelling fluids near saturation or critical points. Moreover, Aspen Plus enables the calculation of properties for multi-component working fluid mixtures, allowing for the simulation of complex thermodynamic cycles [222].

Despite its capabilities, Aspen Plus has some limitations. It lacks the ability to define custom components and does not accurately model real turbine behaviour. The software provides a basic turbine model that only accounts for isentropic efficiency without linking turbine performance to working fluid properties or cycle parameters. Consequently, precise turbine modelling requires additional custom models. Furthermore, Aspen Plus does not include a cooled turbine block, which can lead to unrealistic turbine outlet temperatures exceeding material limits. The software does not allow for incorporating cooling flow into the expander block in distinct cooling stages [300].

Another notable limitation of Aspen Plus is its restricted capability for off-design and dynamic analysis due to the fixed parameters in its blocks and governing equations [301]. Additionally, the simulation does not account for efficiency losses caused by factors such as turbine cooling, vanes, combustion chamber walls, or heat dissipation through piping. These factors can introduce an efficiency penalty of 2-3% in the overall system performance, making real-world validation crucial [302].

3.1.1 Approach to Micro-CHP System Analysis Using Aspen Plus Software

Aspen Plus is a popular and powerful process simulation tool extensively used for modelling, evaluating, and optimising chemical and energy systems, including micro-CHP systems. The methodology employed for analysing micro-CHP systems in Aspen Plus involves several crucial stages, ensuring thorough assessment of system performance, energy efficiency, and environmental effects [303].

1) System Definition and Process Flow Diagram (PFD) Creation

The initial step in Aspen Plus simulation involves specifying the components of the micro-CHP system and constructing a process flow diagram (PFD).

a) Identifying Key System Components

The model is based on the chosen prime mover (such as a fuel cell or micro-gas turbine) along with supplementary components like:

- Fuel processors (e.g., reformers for fuel cells)
- Combustion chambers (for gas turbines)
- Heat exchangers (for cogeneration of heat and electricity)
- Power generation units (fuel cells or micro-gas turbines)

- Exhaust systems (for emissions analysis) [303].

b) Building the Process Flow Diagram (PFD)

The system components are interlinked in Aspen Plus to simulate mass and energy flows, ensuring proper connections between processes, facilitating smooth energy transitions and system operations [303].

2) Thermodynamic Model Selection

To accurately simulate phase equilibrium, reaction kinetics, and thermodynamic properties, a suitable thermodynamic model is selected for each system component.

a) Choosing the Appropriate Thermodynamic Model

- Peng-Robinson (PR): Ideal for hydrocarbon-based fuels.
- Redlich-Kwong (RK): Suitable for high-temperature reactions in the gas phase.
- NRTL (Non-Random Two-Liquid): Used for modelling liquid-phase thermodynamics.
- Electrolyte-NRTL: Applied to aqueous electrolyte reactions, such as those in fuel cells [304].

3) Defining Input Data and Operating Conditions

a) Specifying Input Parameters

- Fuel Composition: Selection of fuels like natural gas, hydrogen, biogas, or syngas.
- Temperature and Pressure Conditions: Defined based on manufacturer specifications and experimental data.
- Flow Rates: Determined for each component to match realistic operational conditions.

b) Modelling Reaction Kinetics and Chemical Reactions

- For fuel cells, methane reforming reactions (e.g., steam methane reforming) are modelled.
- For gas turbines, combustion reactions are represented [305].

4) Simulation and Performance Analysis

a) Running Simulations

- Steady-State Simulations: These are performed initially to assess the system's baseline performance.

- Dynamic Simulations: These are conducted to analyse transient behaviours when needed.

b) Assessing Key Performance Indicators (KPIs)

- Electrical Efficiency (η_e) = (Net electric power output / Fuel input energy) × 100
- Thermal Efficiency (η_t) = (Recovered heat energy / Fuel input energy) × 100
- Total CHP Efficiency (η_{CHP}) = η_e + η_t [306].

5) Sensitivity Analysis and Optimisation

a) Conducting Parametric Studies

- The influence of fuel type (natural gas, hydrogen, biogas) on system efficiency is studied.
- The impact of temperature and pressure on power generation is examined.
- Heat exchanger performance is optimised to enhance cogeneration efficiency.

b) Multi-Objective Optimisation

- Optimisation considers trade-offs between energy efficiency and costs, and focuses on minimising environmental impact [307].

6) Integration with Biofuels and Renewable Energy

Aspen Plus is also employed to model the integration of renewable fuels such as bioethanol, biodiesel, and biogas into micro-CHP systems.

- Exergy Analysis: Used to assess the available useful energy within the system.
- Environmental Benefits: Quantifies CO_2 emissions reduction and evaluates sustainability outcomes [308].

7) Model Validation and Performance Benchmarking

a) Validation of Simulation Results

- Simulation results are validated against experimental data from literature or laboratory studies.
- Cross-checking of results with alternative simulation tools such as MATLAB or EES is performed.

b) Benchmarking Against Conventional Systems

- Comparison of micro-CHP performance with traditional internal combustion engine-based systems.

- Economic feasibility is assessed based on the Levelized cost of energy (LCOE) [309].

8) Conclusion

By following this methodology, Aspen Plus offers a systematic and detailed approach to modelling and optimising micro-CHP systems. This framework ensures a broad assessment of energy efficiency, environmental performance, and economic viability, supporting the development of advanced micro-CHP technologies [222].

3.2 GasTurb14

GasTurb is a powerful simulation software developed to perform precise calculations for gas turbine performance analysis [310,311]. It is widely utilised to model various gas turbine configurations used in both propulsion and power generation applications [310]. Originally developed by Joachim Kurzke in Aachen, Germany, GasTurb has become an essential tool for engineers, researchers, students, and industry professionals. The software enables users to create and analyse design-point and off-design performance models, using data obtained from engine specifications to ensure accuracy in simulations. Additionally, GasTurb facilitates the integration of variable inlet guide vane schedules, further enhancing the precision of off-design performance assessments [310,311].

With a comprehensive set of features, GasTurb allows for parametric studies, numerical optimisations, Monte Carlo simulations, and economic evaluations. The software provides detailed visualisations of gas turbine systems, including labelled component diagrams and thermodynamic relationship charts such as temperature-entropy (T-S), enthalpy-entropy (H-S), and pressure-volume (P-V) diagrams. It also supports the modelling of combined cycle power plants, incorporating gas turbines, heat recovery steam generators, steam turbines, and condensers. Users can further refine analyses by incorporating custom correlations in the form of equations or tabulated data, allowing for more tailored performance evaluations [310].

A key strength of GasTurb is its ability to simulate transient turbine behaviour, mission profiles, and thrust management for commercial aircraft. It also enables engine degradation modelling over time, providing valuable insights into long-term performance monitoring. The software supports batch mode operations and integrates seamlessly with Microsoft Excel for data processing and analysis. Furthermore, GasTurb assists in the initial engine design phase by generating scaled component drawings and estimating engine weight distributions. The software includes tools for stress analysis in circular structures and aerodynamic compressor design using mean-line analysis for multi-stage compressors, helping optimise system efficiency [310].

Despite its advanced capabilities, GasTurb has certain limitations. One notable constraint is its inability to accurately simulate part-load operations when configured to maintain a constant power output. This limitation affects its ability to model dynamic performance variations under fluctuating environmental and operational conditions, which can be critical in real-world applications. Nonetheless, GasTurb remains a highly sophisticated tool for gas turbine performance analysis, offering extensive functionality for both academic research and industrial applications [311].

3.2.1 Methodology of GasTurb14 Software for Micro-CHP System Analysis

GasTurb14 is an advanced simulation tool designed for thermodynamic modelling, performance analysis, and optimisation of gas turbine-based micro-combined heat and power (micro-CHP) systems. The methodology for utilising GasTurb14 in micro-CHP system analysis involves several critical steps, ensuring a broad evaluation of system performance, efficiency, and environmental impact [312].

1) System Configuration and Model Development in GasTurb14

The initial phase involves defining the gas turbine system architecture and setting up key simulation parameters.

a) Selection of Gas Turbine Configuration

GasTurb14 enables the modelling of various micro-gas turbine (MGT) configurations suitable for CHP applications, including:

- Single-shaft MGT, commonly used in micro-CHP systems.
- Two-shaft MGT, offering enhanced operational flexibility.
- Regenerative cycle MGT, improving overall thermal efficiency through heat recovery.

b) Defining Design Point Conditions

The design point represents the nominal operating conditions of the gas turbine, requiring the specification of:

- Compressor pressure ratio (π_c)
- Turbine inlet temperature (TIT)
- Fuel type and composition (e.g., natural gas, hydrogen, or biogas)

- Air mass flow rate and generator efficiency [312].

2) Thermodynamic Modelling and Cycle Analysis

GasTurb14 employs fundamental thermodynamic principles to model and assess gas turbine cycles under various operating conditions.

a) Modelling the Brayton Cycle for Micro-CHP Applications

- The simple Brayton cycle, consisting of compression, combustion, and expansion.
- The regenerative Brayton cycle, incorporating heat recuperation to improve efficiency.
- The intercooled and reheat cycle, enhancing system performance at higher loads.

b) Performance Metrics and Efficiency Evaluation

GasTurb14 calculates essential performance indicators, including:

- Thermal efficiency (η_{th}) = Net work output / Heat input
- Specific power output (W_{spec}) = Power generated per unit mass flow
- Exergy efficiency (η_{ex}) = Useful exergy output / Total exergy input [313].

3) Off-Design Performance Assessment

GasTurb14 facilitates the analysis of system behaviour under variable operating conditions.

a) Parametric Studies on Part-Load Operation

- Role of atmospheric temperature and pressure changes in determining system performance.
- Effects of compressor pressure ratio on turbine efficiency.
- Influence of fuel flow rate and TIT variations on power output.

b) Development of Performance Maps

- Generation of compressor and turbine efficiency maps to assess system behaviour under real-world conditions.
- Optimisation of operating strategies for improved load adaptability [310].

4) Heat Recovery and CHP System Integration

While GasTurb14 does not model heat recovery systems directly, it provides exhaust gas characteristics essential for CHP system design.

a) Estimating Exhaust Heat Availability

- Exhaust gas temperature (Texh) and mass flow rate determine available thermal energy.
- Assessment of heat exchanger effectiveness for cogeneration applications.

b) Calculation of CHP Efficiency

- CHP efficiency (η_{CHP}) = (η_{el} + η_{th}) × 100
- Comparative analysis of simple cycle vs. regenerative cycle CHP systems [77].

5) Fuel Analysis and Emissions Assessment

GasTurb14 supports fuel flexibility and evaluates combustion performance for different fuels.

a) Fuel Type and Combustion Characteristics

- Simulation of natural gas, biogas, hydrogen, and syngas combustion.
- Calculation of NO_x, CO, and CO_2 emissions based on equivalence ratio.

b) Environmental and Sustainability Considerations

- Exergy-based emissions reduction analysis.
- Comparative study of fossil-fuel-based vs. biofuel-based micro-CHP systems [314,315].

6) Validation and Benchmarking

GasTurb14 results are validated through:

- Experimental data from laboratory testing and manufacturer specifications.
- Cross-comparison with Aspen Plus simulations for hybrid system modelling.

a) Comparative Assessment with Conventional CHP Technologies

- Performance benchmarking against internal combustion engine-based CHP systems.
- Economic evaluation, including Levelized cost of energy (LCOE) analysis [316].

7) Conclusion

GasTurb14 offers a robust framework for the modelling, optimisation, and analysis of micro-gas turbine-based CHP systems. By incorporating thermodynamic modelling, off-design analysis, fuel flexibility, and emissions evaluation, it serves as a valuable tool for researchers and engineers in the development of next-generation micro-CHP technologies.

4. CHAPTER 4: RESULTS, VALIDATIONS, AND DISCUSSIONS

This chapter outline the key research outcomes, with a primary focus on the performance evaluation, fuel flexibility, and techno-economic feasibility of micro-CHP systems, including detailed validations against existing models and experimental data. The first section 4.1 discusses the low-carbon fuelled MGT-CHP system coupled with PEM electrolyser and fuel cell units, exploring the flexibility and operational performance of a 5.5 kW MGT-CHP configuration for domestic applications. The system is designed to simultaneously produce heat and electricity, where hydrogen (H_2) is generated through a PEM electrolysis unit for combustor fuelling, while a PEM fuel cell supports electricity generation during start-up. A range of fuels, including H_2, hythane (20% H_2 + 80% CH_4), natural gas (NG), and methane (CH_4), is used to evaluate thermal and electrical efficiency, alongside CO_2 emission avoidance.

The second section 4.2 presents the performance and process simulation of a 3.5 kWe MGT system designed for household applications. Simulated using GasTurb 14 and Aspen Plus software, the study investigates fuel flexibility and performance results with different fuels—NG, H_2, and hythane. The effects of fuel type, H_2 concentration, fuel/air mass flow rates, combustor pressure, and turbine inlet temperature (TiT) are considered, with both design and off-design performance points analysed.

Finally, section 4.3 evaluates four major micro-CHP prime movers (micro-gas turbine, gas engine, Stirling engine, and fuel cell) in terms of their performance and current technologies. The most suitable options for household applications are identified through a PESTLE risk analysis and a Multi-Criteria Decision Analysis (MCDA), determining the prime movers with the highest potential for residential use based on political, economic, social, technological, legal, and environmental factors.

4.1 Low-carbon fuelled MGT-CHP system coupled with PEM electrolyser and fuel cell units: A fuel flexibility and performance study

This section has focused on the performance and fuel flexibility analysis of a 5.5 kW MGT-CHP system coupled with a proton exchange membrane (PEM) electrolysis cell and a fuel cell unit for domestic applications. The simulation study includes an MGT unit that produces heat and electricity, a low-temperature PEM electrolysis of

H_2O to produce H_2 fuel for the combustor, and a PEM fuel cell to generate electricity during system initialisation. The MGT unit in this study uses H_2, hythane (20% H_2 + 80% CH_4), natural gas (NG) and methane (CH_4) fuels to investigate the thermal and electrical efficiency and CO_2 emission avoidance for each fuel utilisation. The result shows that the combustion of H_2 and hythane in the MGT combustor produces almost the same amount of nitrogen oxides (NOx) due to the lower reaction temperature of the combustor. Nearly 7% of CO_2 and CO emissions were avoided by replacing NG with hythane. CO_2 and CO emissions were avoided by burning H_2 instead of other fuels. Higher thermal efficiency was seen on the H_2-fuelled MGT system. However, higher end-use costs were observed for the MGT system running on both H_2 and hythane fuels due to the higher purchase price of both fuels. The addition of a recuperator promoted lean combustion, which improved the overall efficiency of the proposed system. The outcome of the studied work achieved an efficiency of 82% for PEM electrolysis of H_2O and an MGT-CHP combined efficiency of 96%. Figure 4-1 shows the graphical abstract of this section.

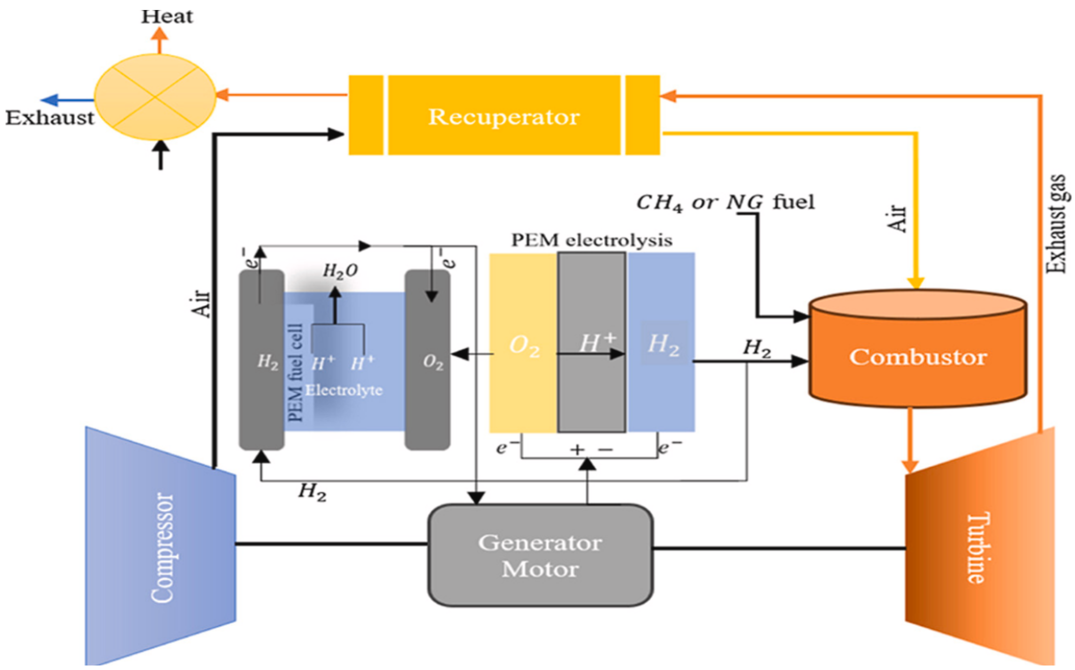

Figure 4-1: Graphical abstract of this section [317]

4.1.1 Simulation

To achieve the target power of 5.5 kW, *Aspen Plus process simulation software was used with* H_2, CH_4, *NG and hythane* as combustion fuel. A rigorous reactor (RGibbs) was considered to simulate the fuel combustion and electrolysis of H_2O using proper electrochemical reactions in the chemistry ID. Other Aspen Plus core components included in this simulation are pumps, compressor, turbine, recuperator (heat exchanger), switch, mixer, splitter, and calculator block. The upstream intake parameters of the proposed system are shown in Table 4-1. While the simulation method of this proposed system is explored in the below scenarios:

- Aspen plus process simulation of an existing MGT-based micro-CHP system to improve knowledge of the proposed model.
- Aspen plus process simulation for the proposed model which includes a micro-CHP system running on hydrogen (H_2), hythane, NG and CH_4.

Table 4-1: MGT combustor inlet and outlet parameters

Property/Parameter	Value	Unit
MGT combustor intake fuel pressure	2.9	bar
MGT combustor intake fuel temperature	970	K
Air mass flow rate	0.053	kg/s
MGT burner exit temperature	1323.4	K

1) Process simulation of existing micro-CHP system and proposed innovative system in Aspen plus

The process simulation of the existing micro-CHP system and the proposed model were carried out in Aspen Plus and both the Peng-Robinson and Non-Random Two-Liquid (NRTL) equations of states were employed with mixed as the only sub stream. The assumptions considered in both process simulations are described below:

- All processes are in steady state condition.
- Intake feed temperature and pressure is ambient and atmospheric conditions.
- The pressure drop at each stage is minimal.
- 78% nitrogen, 21% oxygen, and 1% argon mole flow are the compositions of air fed to the system.
- Dry NG is composed of 96% CH_4 (methane), 2% C_2H_6 (ethane), 0.60% C_3H_8 (propane), 0.18 C_4H_{10} (isobutane), 0.12% C_4H_{10} (n-butane), 0.14% C_5H_{12} (isopentane), 0.06% C_5H_{12} (n-pentane), 0.10% C_6H_{14} (hexanes) and 0.80% C_7H_{16} (heptanes) [318].
- Oxides of nitrogen (NOx) include nitric oxide (NO), nitrogen dioxide (NO_2), nitrous dioxide (N_2O) and nitrogen pentoxide (N_2O_5).
- 80% of CH_4 and 20% of H_2 are composition of hythane.
- Electrolysis of H_2O to generate H_2 for hythane using the electricity generated from the proposed system.
- H_2 fuel cell to generate electricity for the motor during the start-up of the proposed system.

- Air fed to the combustor is preheated by a recuperator (heat exchanger) unit to maximise the overall efficiency.
- The efficiency (thermal and power) MGT-CHP is about 96%.

Figure 4-2 shows a NG-operated micro-CHP system for heat and power production. In the process flow diagram, air at 0.053kg/s is compressed to a pressure of 2.9 bar in the compressor and sent to the recuperator system to increase the temperature to 970K. Pressurised hot air from the recuperator is combusted with pressurised NG at a ratio of 106:1 in the combustion chamber (CC). The hot gas leaves the CC at a temperature of 1323.4K to a turbine where electricity is generated. The hot gas in the turbine created a rotatory motion that turns an electricity generator for the conversion of mechanical energy to electrical energy with 5.5 kW power output. The low-pressure hot flue gases exiting the recuperator preheat the combustor air intake before the heating of the water (H_2O) molecule in another heat exchanger. In a hot H_2O heating system, the cold H_2O from the storage tank is pressurised by a pump before absorbing heat from the flue gases. This is a continuous cycle to provide hot water and heat the environment while the micro-CHP system is running. During the system start-up time, electrical energy from the grid is needed to ramp up the compressor for air intake with the use of an electric generator which in turn, works as a motor. In the final stage, the exhaust gas which is a mixture of carbon dioxide (CO_2), nitrogen gas, oxides of nitrogen (NOx) and others from the H_2O heater is discharged into the environment.

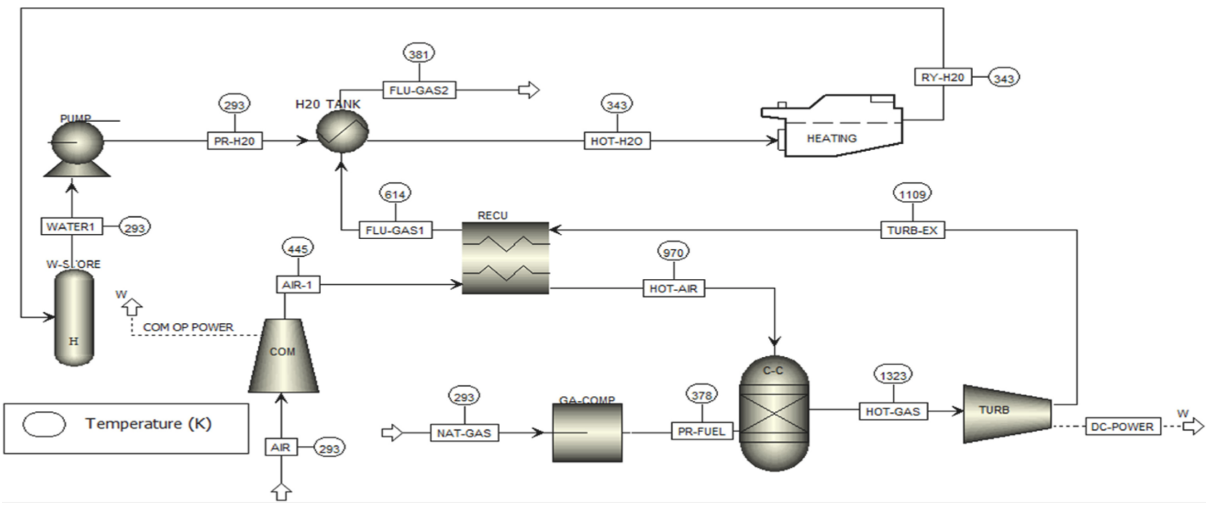

Figure 4-2: Aspen plus process diagram of MGT-CHP system operating with NG.

Similar to a conventional micro-CHP system, the proposed model shown in Figure 4-3 uses H_2 gas, hythane, NG and CH_4 gas as fuel. Proton exchange membrane (PEM) electrolysis of H_2O and H_2 fuel cells were introduced to generate H_2 feedstock and electricity for the motor during start-up time. The motor which is also an electric generator spins the compressor during the initiation period to suck air in and increases the pressure. Unlike a conventional micro-CHP system, the proposed model has a fuel switching unit, mixer, splitters and motor-electricity generator. The fuel-switching unit allows one fuel to be used at a time to monitor the heat output of the combustion chamber (CC). The mixer (mix) mixes both the H_2 feed and the H_2 by-product of the PEM electrolyser unit to feed CC. The motor rotates the compressor at a speed of 240000 rpm during the kick-off time. While a controlled amount of O_2 gas into the PEM fuel cell (PEMFC) is possible using an oxygen (O_2) splitter. Similarly, the H_2 gas splitter controls the flowrate of H_2 gas to the mixer and PEMFC to generate electricity for the motor. The calculator block estimates the power output of the proposed system by subtracting the input powers of the air and gas compressors and a pump from the output power of the turbine. The rest of the unit has the same working principle as the conventional micro-CHP system. This developed system also has the potential to increase the output power by reducing the heat production in applications where less thermal energy is needed.

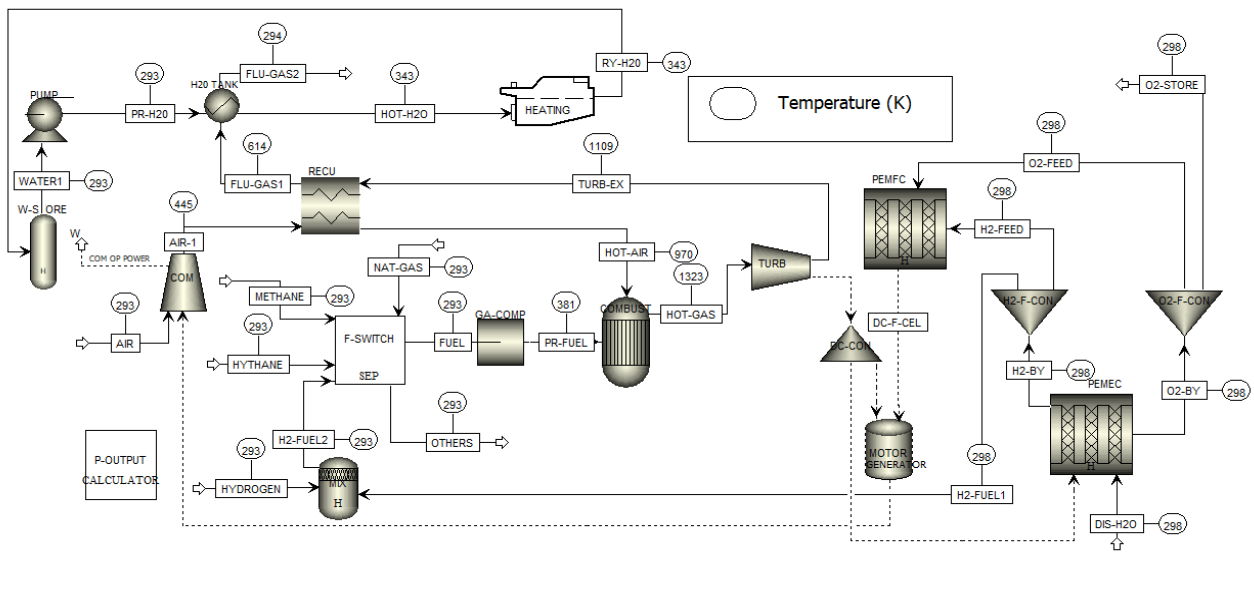

Figure 4-3: Aspen plus process diagram of MGT-CHP system coupled with PEM electrolyser and fuel cells.

4.1.2 Results

Table 4-2 illustrates the process simulation results. To reduce the percentage of CO_2 emissions in a micro-CHP system, a mixture of CH_4 and H_2 (hythane) should be used as the combustion fuel. Whereas the absence of CO_2 emissions from a micro-CHP system requires the burning of pure H_2 fuel in the combustion chamber. Using the same mass flow rate of hythane as NG, the heat output of the combustor was relatively higher, while smaller changes in heat output were observed in the burner operating with CH_4 as the fuel. Combustion of H_2 at the same mass flow rate as NG was extremely higher and increased the amount of NOx emissions and the overall efficiency. Thus, keeping the same fuel mass flow rate means that MGT combustors with larger bore diameters and lengths are needed for both hythane and H_2 to promote longer reactant residence time. To maintain the same combustor heat output for all fuels at a constant oxidant flow rate, the air-to-fuel ratio of 106:1 for NG and CH_4, 135:1 for hythane (80% CH_4 and 20% H_2) and 252:1 for H_2 were utilised. This approach reduced NOx formation and eliminated short reactant residence time which can lead to combustion outside the burner. Considering the mass flow rate of H_2 fuel into the combustor, the introduction of a small-scale renewable energy system such as a solar or wind energy system may be necessary to increase the H_2 by-product of the PEMEC. For example, utilising the power output of the developed model, a maximum of 40% of H_2 can be produced for hythane fuel. The deployment of both PEMEC and PEMFC has shown that it is possible to avoid the need to sell the generated electricity to the grid at a lower price and buy at a higher price to run the motor at 240,000 rpm during start-up. An increase in the power output of the model was possible by reducing the discharged turbine pressure since the downstream units are not pressure-dependent. For both the combustor and generator units operating at the listed air-to-fuel ratio in Table 4-2, a thermal energy output of 26.9MJ/h and a net power output of 5.5kW were recorded.

Table 4-2: Emission result of CC operating at 3 bar pressure and 1323.4K temperature at 26.9MJ/h and 5.5kW energy output.

Fuel % NG	Fuel % CH_4	Fuel % H_2	Prod. CO_2 kg/h	Prod. H_2O kg/h	Prod. O_2 kg/h	Prod. N_2 kg/h	Prod. NOx kg/h	Air-to-fuel ratio
100	0	0	5	5.7	31.4	148.8	0.09	106:1
0	100	0	5	5.7	31.3	148.8	0.09	106:1
0	80	20	3.1	6.8	31.8	148.8	0.09	135:1
0	0	100	0	8.5	32.5	148.8	0.095	252:1

1) Fuel analysis of the simulated hybrid system

During the process simulation of the integrated system running on pure H_2, hythane, NG and CH_4, the combustion chamber outlet temperature is maintained at 1323.4 K. At the same mass flow rate of 0.5 g/s, the heat output of the combustion chamber was found to be 39.4 kW for pure H_2, which was much higher than 13.9 kW for hythane, 7.4 kW for NG, and 7.5 kW for CH_4 kW. The adiabatic flame temperature of H_2 is higher than hythane, NG and CH_4 resulting in higher heat production. However, H_2 produced a lower electrical output (5.03 kW) compared to hythane NG and CH_4 because of its low density. As shown in Table 4-3, the molar and mass enthalpy of the combustion chamber exhaust gas operating with pure H_2 had negative values compared to other fuels because the exothermic reaction releases more energy. By comparing the molar and mass entropy of the combustion chamber exit gases, H_2 has lower values because of its lightweight and movement flexibility [318]. The simulated system shows that the mass flow rate of H_2 and hythane can be reduced to achieve the same heat output of other fuels (NG and CH_4). However, reducing the mass flow rate of both fuels (H_2 and hythane) will further decrease the electrical power output of the MGT-CHP system. Thus, using the same mass flow rate of CH_4 for H_2 fuel to the MGT combustor, and recovering more heat for distilled H_2O production, more H_2 fuel can be produced via the electrolysis of H_2O in an application with less heat requirement. In this approach of substituting NG or CH_4 for pure H_2 fuel for more heat production, a larger micro combustor size with coolant addition such as steam or N_2 may be required to minimise thermal combustor wall stress and prevent exhaust gas exceeding 1323K temperature. The simulated system achieved an efficiency of 96% for CHP and 82% for the electrolysis unit. Figure 4-4 shows a thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG and CH_4. From the displayed graph, low-density and higher energy-density fuels produced more heat and less power output.

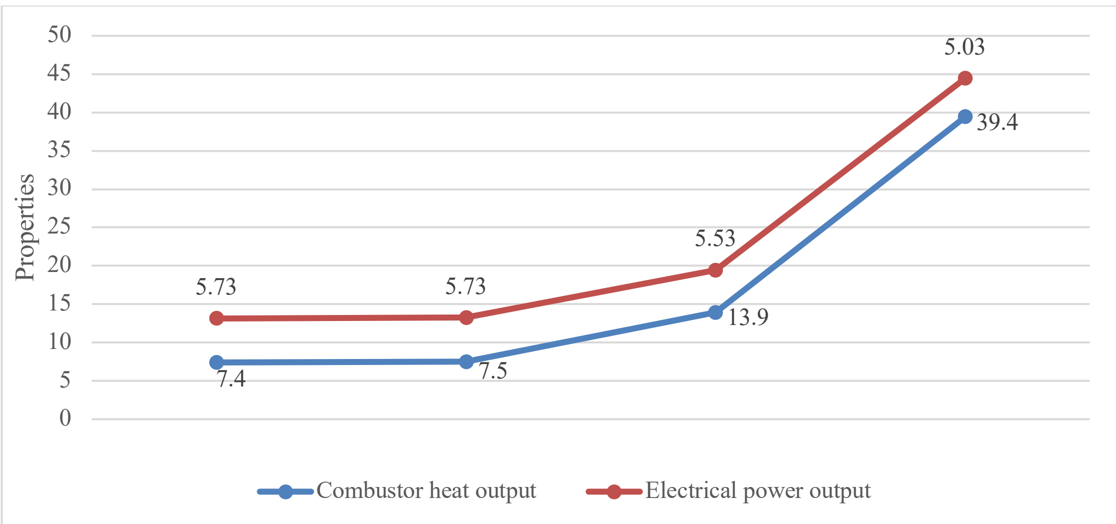

Figure 4-4: Thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG, and CH_4.

Table 4-3: Comparison of combustor exit gas running on H_2, hythane, NG and CH_4 fuel at 0.5 g/s mass flow rate.

Properties	H_2	Hythane	NG	CH_4	Unit
Combustor heat output	39.4	13.9	7.4	7.5	kJ/s or kW
Electrical power output	5.03	5.53	5.73	5.73	kW
Molar Enthalpy of the combustor exit gas	-84.5	12106.3	15361.1	15304.5	kJ/kmol
Mass Enthalpy of the combustor exit gas	-3.1	429.6	539.6	537.7	kJ/kg
Molar Entropy of the combustor exit gas	38.4	41.1	41.7	41.7	kJ/kmol-K
Mass Entropy of the combustor exit gas	1.4	1459.5	1.5	1.5	kJ/kg-K
Enthalpy Flow of the combustor exit gas	-0.2	23	28.9	28.8	kJ/sec
Average	27.1	28.2	28.5	28.5	MW

2) NOx emission analysis

The simulated hybrid MGT-electrolysers system with an output power of 5.5 kW requires larger H_2 and hythane combustors' size to operate smoothly as NG and CH_4 based MGT systems with low NOx formation. The result shows that NOx production was about 0.09 kg/h for all four fuels at lean combustion. For example, thermal NOx formation occurs at a reaction temperature above 1773.15 K [27]. However, CFD simulation software may be required to properly investigate the NOx amount on each fuel of the simulated system. Nonetheless, the addition of steam or nitrogen may be required for H_2 combustion to control the NOx formation rate. The use of these renewable fuels such as H_2 and hythane has been found to provide efficient MGT performance and significantly reduce CO_2 emission. Designing flameless burners and maintaining H_2-controlled flame temperatures are two key points in the development of H_2 and hythane systems in this field (MGT-based micro-CHP system).

The simulated model is validated part by part with data listed in the literature. Comparing the MGT-CHP unit of this study with another MGT system installed at Staffordshire University, a marginal difference was recorded on combustors operating with H_2 and hythane fuels. The difference was attributed to the higher heat output of combustors operating with both fuels. For instance, NOx emissions <27 ppm (part per million) at 15% O_2, electrical power output of 3kW, electrical efficiency of 16%, and a combined efficiency of >94% were reported for the MTT MGT-CHP system [231]. For this simulated system, higher electrical and lower thermal efficiencies were recorded. Higher electrical power output makes this model more suitable for small-scale units' where higher electrical energy is required. Comparing the efficiency of the PEMEC unit with *Sapountzi, et al.* studied work; both studies achieved nearly the same efficiency. For example, PEMEC efficiency between 65% – 82% was reported by *Sapountzi, et al* [319].

3) Environmental assessment and economic analysis

H_2 has many advantages over traditional fuels. The main advantage of H_2 and H_2-rich fuels in MGT is lower GHG emissions [320]. In recent years, H_2 and a mixture of H_2 and CH_4 (hythane) have been used in MGT systems [228]. This section presents the environmental analysis of renewable fuels such as H_2 and hythane with non-renewable fuels like NG or CH_4. The introduction of H_2 and hythane in the MGT-based micro-CHP system was found to reduce GHG emissions. The simulation results show that when producing the same power (i.e. 5.5 kW), H_2 releases zero CO_2 emission. While CO_2 emission of 3.1 kg/h for hythane, 5 kg/h for NG and CH_4 was seen. As current MGT-CHP systems use NG as fuel, GHG emissions and environmental pollution will continue to be on the rise. Although, NG-based MGT systems can still be used as a transitional fuel for coal and oil due to its lower CO_2 emissions, but not the most optimal energy solution [28]. To reduce carbon emissions and increase energy efficiency, H_2 stands out as one of the most potential energy carriers due to its CO_2-free and high energy density. Several countries, such as UK, Germany, Japan, USA, and China have proposed strategies to develop H_2-based energy technologies [321]. At the same time, H_2 research increased, including its production, storage and utilisation [322]. Connecting H_2 energy to MGT-CHP systems offers the possibility of even greater efficiency, reliability and lower emissions for residential and commercial applications. Therefore, a H_2-based MGT-CHP system has been considered a promising alternative to fossil fuel-based cogeneration systems in terms of efficiency improvement and reduction of carbon emissions [28].

The price of fuel is one of the most important parameters that has a direct relationship with the economic benefits of the MGT-CHP system operating with low-carbon fuels because it directly affects the operational cost. This section presents the economic analysis of H_2 and hythane with other fuels such as NG and CH_4. H_2 has a lot of potential for sustainable development but also has some disadvantages from an economic point of view because the economics of 100% H_2 dependence is still unknown and the higher cost of H_2 fuel reduces competitiveness [323]. The purchase price of H_2 is much higher compared to other fuels (hythane, NG and CH_4). For instance, green H_2 costs between \$5.10/kg to 10.3/kg in contrast to grey H_2

(obtained from hydrocarbon reforming methods without carbon capture and storage (CCS) units) with a sales price of $1.89/kg [324]. In addition, H_2 production from NG will increase import by 30% [325]. In this regard, it would be beneficial to build H_2 production plants closer to CHP systems to mitigate storage and transportation costs and challenges [324,325]. By comparing H_2 and hythane from an economic perspective, it is more cost-beneficial to use hythane instead of 100% H_2 for MGT-CHP systems during the transition period. However, burring H_2 and CH_4 (hythane) at a ratio of 20:80 can reduce carbon emissions only by 7% [326]. In addition, electricity from the grid costs $0.5/kWh in the UK and $0.54/kWh in the USA [327]. While the feed-in tariff (FIT) is about $0.12/kWh or lower. By using produced electricity from the simulated system to produce H_2 rather than selling it at a cheaper rate to the grid, between 6 – 7% of GHG emissions and 43% end-user cost increase can be avoided. To achieve a successful H_2 economy, it is recommended to switch to more efficient and environmentally friendly H_2 production technologies.

4.1.3 Discussion:

A natural gas (NG), methane (CH_4), hythane (H_2+CH_4) and hydrogen (H_2) fuelled MGT coupled with a PEM electrolyser and fuel cell units was process simulated as a combined system. The developed system produced H_2 for hythane fuel via the electrolysis of H_2O and electricity using a fuel cell system. By producing H_2 for hythane and electricity for electrical units, selling generated electricity to the grid at a cheaper rate and buying at a higher price were avoided. Low NOx emissions from both hythane and H_2 fuels showed that by burning any of these fuels with the addition of coolants such as H_2O in the combustor, the same NOx levels of NG-based MGT system can be achieved. Replacing NG with hythane reduced CO_2 emission by 7%, while the absence of CO_2 emission was attained from H_2 combustion. The findings also suggested the application of renewable solar or wind energy systems to the simulated system operating with H_2 fuel to increase the production rate. CFD simulation of MGT-CHP combustors operating with hythane and H_2 fuel with the addition of coolant was recommended to properly investigate NOx formation and thermal stress of the combustors' walls. An increase in the size of the MGT-CHP combustor operating with H_2 or hythane at the same fuel mass flow rate was also proposed to improve the reactant residence time and prevent combustion outside the combustor. Efficiency of 96% for CHP and 82% for electrolysis were achieved from the developed hybrid system.

4.1.4 Validation

This study validates the proposed MGT-CHP system (Present Study) by benchmarking its performance against the micro gas turbine (MGT) system from MTT [231], which was purchased and installed at Staffordshire University. Both systems have several similar operating conditions, however, the MTT system is designed exclusively for natural gas (NG) as its fuel source. Consistent with industry standards, validation for both systems was performed using natural gas (NG) as the baseline fuel, facilitating a direct and reliable comparison of performance and efficiency. In addition to NG, the proposed system offers enhanced flexibility, with the capability to operate on hydrogen (H_2), hythane (20% H_2 and 80% CH_4), and pure methane (CH_4), supporting future-ready advancements in MGT-based CHP technologies. Performance predictions for alternative fuels were extrapolated from NG-based results, providing meaningful insights into the system's potential under varying fuel scenarios.

Both systems share several key operating parameters—such as an exit temperature of 1050.25°C (1323.4 K) and a rotor speed of 240,000 rpm—but the proposed system demonstrates superior performance across multiple areas when benchmarked with NG. The below Table 4-4 shows the similar operating conditions shared by the proposed system and the Staffordshire MTT system, allowing for a meaningful comparison.

Table 4-4: Aligned Operating Parameters between the Proposed and MTT Systems

Property/Parameter	Proposed system Value	MTT Value	Unit
MGT combustor intake fuel pressure	2.9	2.86	bar
MGT combustor intake fuel temperature	970	970	K
Air mass flow rate	0.053	0.053	kg/s
MGT burner exit temperature	1323.4	1323.4	K

The validation confirms that the proposed system achieves a higher net electrical efficiency (23% compared to 16% for the Staffordshire MTT system) and an overall CHP efficiency of up to 96% under NG operation, marking a significant improvement in energy output and utilization. A critical advantage of the proposed system is its future-proof fuel flexibility. While NG remains the primary focus of validation and deployment, the system is also designed to operate with hydrogen, hythane, and methane, offering considerable environmental benefits. Hydrogen operation, for instance, eliminates CO_2 emissions entirely, while hythane reduces CO_2 emissions by around 7% compared to NG. Methane, being the main component of NG, offers a seamless transition fuel option, with similar operational performance. Emission performance, validated with NG, shows the proposed system achieving markedly lower NOx emissions than the Staffordshire MTT system. While the MTT system records NOx emissions of <27 ppm @ 15% O_2, the proposed system achieves NOx levels of approximately 0.09 kg/h with NG, CH_4, and hythane, and 0.095 kg/h with hydrogen. This lower emission footprint underscores the environmental advantage of the proposed design, especially when running on NG, the most widely available fuel.

Thermal output validation further highlights improvements: with NG, the proposed system delivers enhanced heat output compared to the Staffordshire MTT system's 15.6 kW thermal capacity. This advantage becomes even more pronounced when operating with hydrogen, where the combustor heat output reaches 39.4 kW, broadening application potential in CHP systems. The Figure 4-5 below shows the overall output comparison between the simulated system and the MTT system running on NG.

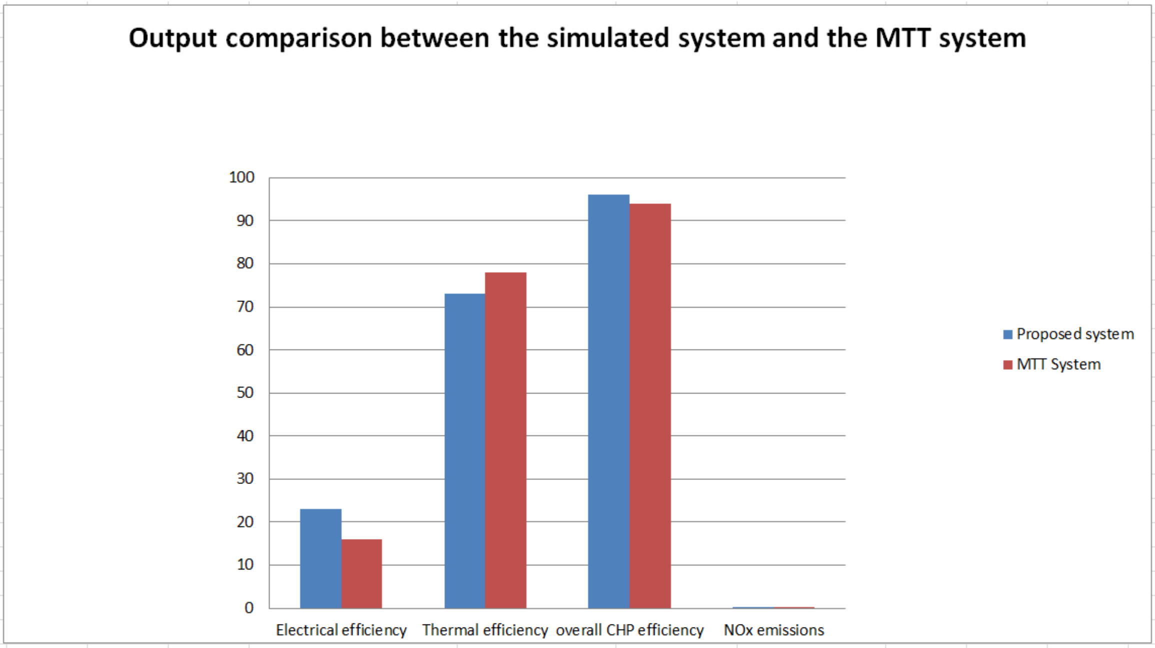

Figure 4-5: Comparison of Output Results: Proposed System (Present Study) vs. MTT System

In addition, the proposed system incorporates a hybrid approach—combining MGT technology with a PEM electrolyser and fuel cell—enabling on-site hydrogen production and enhancing energy self-sufficiency, even under NG operation. This design allows the system to not only perform optimally with NG but also transition smoothly to low-carbon fuels, supported by renewable energy sources like solar and wind, positioning it as a cornerstone for sustainable future energy infrastructures.

In summary, while the Staffordshire University MTT system provides a valuable benchmark for NG-based MGT-CHP applications, the proposed system offers significant advancements in NG validation performance—alongside unmatched flexibility for hydrogen, hythane, and methane operation. This positions the proposed system as a key enabler of both near-term efficiency improvements and long-term decarbonisation goals.

4.2 MGT systems for clean heat and power generation for domestic applications: A fuel flexibility and performance study

This section is reporting the performance and process simulation of a 3.5 kWe MGT system that provides heat and power for households' applications. The fuel flexibility and performance of this unit are simulated using GasTurb 14 and Aspen Plus software for different fuels including, Natural gas (NG), Hydrogen (H_2), and hythane (20% H_2 + 80% CH_4). The effects of the fuel type and H_2 concentration, as well as fuel/air mass flow rates, combustor pressure, turbine inlet temperature (TiT), and performance analysis of the cycle at design and off-design points are investigated. The cycle efficiency for H_2, hythane, and NG MGT cycles is calculated to be 29%, 27%, and 26%, respectively. The result shows that burning H_2 in MGT combustors raises nitrogen oxide (NOx) formation, but it confirms lower CO_2 emission as compared to burning NG and hythane. The power-specific fuel consumption (PSFC) of 100% H_2 present is lower than that of 100% NG and hythane because of its higher energy content and lower fuel density. Considering the carbon-neutrality of H_2 and hythane renewable fuels they seem to be suitable alternative fuels for MGT systems if these fuels are generated with low-emission technologies. The performance results of the MGT engine and numerical inputs using analytical methods show that a micro-CHP system with overall efficiencies of above 85% is possible for these alternative fuels.

4.2.1 Simulation

Numerous studies have extensively analysed and evaluated MGT technology to determine the optimal outcomes from both performance and process simulation perspectives. To achieve the desired power output of 3.5 kWe, a single-spool Turboshaft engine with a recuperator (as shown in Figure 4-6) was selected. The design and off-design performance of MGT operating on NG, H_2, and hythane were assessed using Gasturb14, while Aspen Plus software was employed to simulate the thermodynamic process of these fuels. Each fuel type was introduced into the simulation models with the inlet properties specified in Table 4-5.

Table 4-5: 1 Spool Turboshaft engine inlet properties data

Property/Parameter	Value	Unit
Ambient Pressure	101.325	kPa
Ambient Temperature	288.15	K
Mass flow rate	0.06	kg/s
Compressor Pressure ratio	3	-
Isentropic Compressor Efficiency	0.75	-
Isentropic Turbine Efficiency	0.70	-
Intake Pressure ratio	0.98	-
Burner Exit Temperature	1250	K
Burner Design Efficiency	0.999	-
Overboard Bleed	0	kg/s
Mechanical Efficiency	0.98	-
Burner Pressure Ratio	0.95	-
Turbine Exit Duct Pressure Ratio	0.98	-

The central goal of this research is to establish an efficient and a viable MGT system powered by NG, H_2, and hythane, tailored for household and limited-capacity energy needs. To ensure a fair comparison of performance and process simulation across different fuels, the target power output was uniformly set to 3.5 kWe. Achieving an optimal MGT configuration requires careful consideration of critical parameters, such as air intake, pressure ratio, and combustion chamber exit temperature. These factors significantly influence system efficiency and performance, making them key variables in the optimisation process. Initially, a reference case was established using 100% NG as the fuel, followed by a similar assessment for H_2 and hythane.

4.2.2 Results

Initially, this section outlines the findings derived from Gasturb14, which are then complemented by an in-depth evaluation of the Aspen Plus simulation outcomes.

1) Gasturb14

Gasturb14 was utilised to evaluate both the design and off-design performance of the selected fuels. Given that a 3.5 kWe engine is relatively small compared to conventional MGT used in CHP applications (which typically generate over 1000 kWe), a single-spool Turboshaft engine with a recuperator was chosen for the simulations. The cycle diagram for this engine configuration is illustrated in Figure 4-6. The system layout includes key stations: (1) ambient conditions, (2-3) compressor inlet and outlet, (35) cold-side exit of the heat exchanger, (4) burner exit, (5) turbine exit, (6-7) heat exchanger hot-side inlet and exit, and (8) exhaust exit.

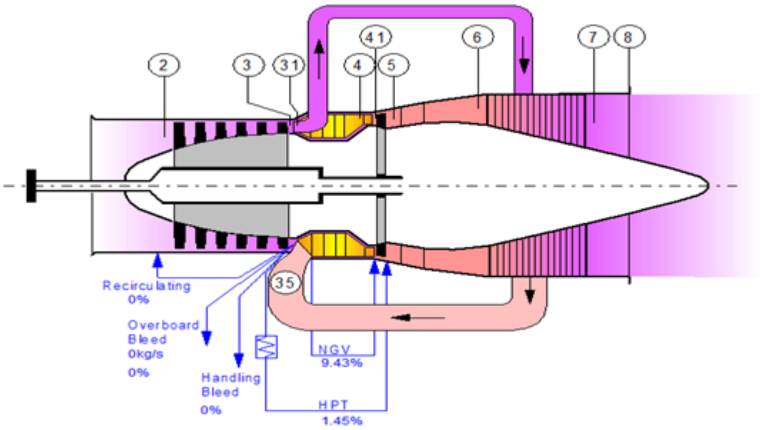

Figure 4-6: 1 Spool Turboshaft engine with regenerative cycle diagram [310]

To achieve the 3.5 kWe output in a household-scale MGT using NG, H_2, and hythane, a minimal air intake flow of 0.06 kg/s was selected to mitigate NOx emissions while maintaining a burner exit temperature of 1250 K. This temperature was chosen to prevent excessive thermal stress and ensure the longevity of turbine components, while still delivering the required power output. The simulation input data for all fuel types, as outlined in Table 4-5, were incorporated into Gasturb14 for evaluation. The results of the design cycle simulations for MGT operating on NG, H_2, and hythane are summarised in Table 4-6.

Table 4-6: Comparison of design point calculations results for NG, H_2, and hythane

Properties	NG	H_2	Hythane	Unit
Shaft Powered	3.568	3.501	3.543	kW
Power Specific Fuel Consumption (PSFC)	0.3697	0.1520	0.2236	kg/kW*h
Combustor Heat Output	4.610	27.42	8.89	kW
Fuel Flow (WF)	$3.6268*10^{-4}$	$1.4814*10^{-4}$	$2.8325*10^{-4}$	Kg/s
Heat Exchanger Pressure Ratio (P35/P3)	0.98500	0.98500	0.98500	
NOx severity parameter (S NOx)	0.99998	1.00551	0.999	-
(Core) Nozzle Throat Mach Number (XM8)	0.1696	0.2074	0.1782	
Geometric (Core) Nozzle Throat Area (A8)	0.0011	$9.209*10^{-4}$		m²
Exhaust Pressure Ratio (P8/Ps8)	1.02000	1.03000	1.02500	
Bleed Air Flow/Mass Flow (WBID/W2)	0	0	0	
Inlet Pressure Ratio (P2/P1)	0.98000	0.98000	0.9800	
LPT Nozzle Guide Vane Cooling Air/W2 (WCLN/W2)	0.9426	0.9426	0.9426	
LPT Rotor Cooling Air / W2 (WCLR/W2)	0.01450	0.01450	0.1450	
Burner Loading in % of the cycle design point value	100	100	100	%
Turbine Exit Duct Pressure Ratio (P6/P5)	0.9800	0.9800	0.9800	
Electric Power (PW_gen)	3.5	3.5	3.5	kW

The burner exit temperature was consistently set at 1250 K across all fuels to align with material constraints and ensure comparability. However, due to H_2's higher adiabatic flame temperature, an MGT running exclusively on hydrogen might exhibit slightly elevated burner exit temperatures. Despite this, the simulation results in Table 4-6 confirm that H_2 can generate the same shaft power as NG and hythane while demonstrating a lower fuel mass flow rate and PSFC, leading to potential fuel savings.

Figure 4-7 illustrates that PSFC is initially higher during start up but stabilises during steady-state operation. This indicates that gas turbines achieve peak efficiency during continuous operation rather than under frequent start-stop conditions. Among the tested fuels, H_2 exhibits the lowest PSFC because of its substantial energy storage capacity and low mass flow requirement. Under continuous operation at 3.5 kWe, the PSFC values recorded were 0.1520 kg/kWh for H_2, 0.254 kg/kWh for hythane, and 0.3915 kg/kWh for NG.

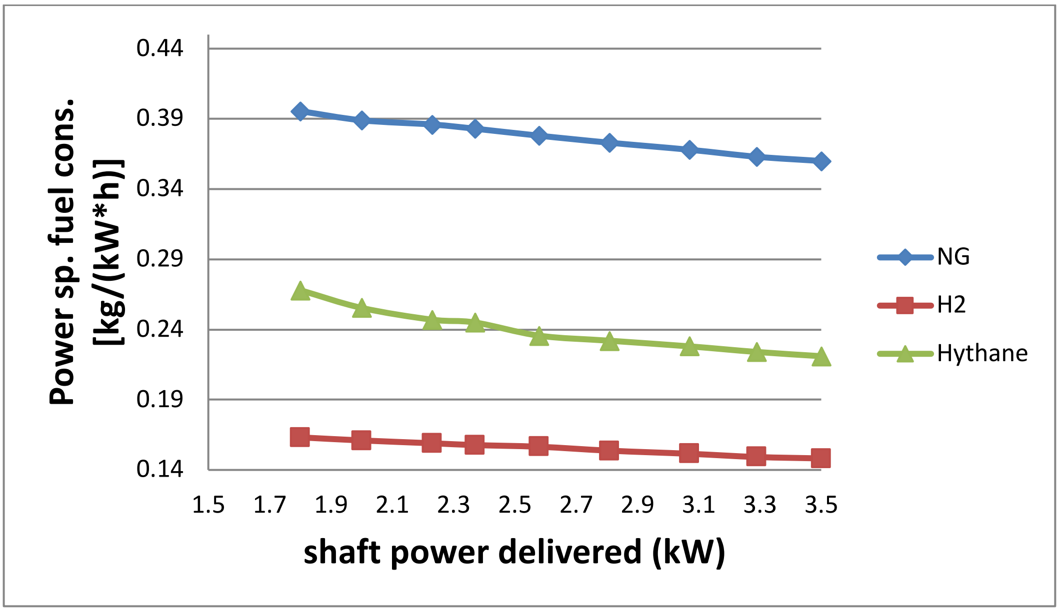

Figure 4-7: Variation of PSFC with shaft power delivered for NG, H_2, and hythane

The severity index for NOx emissions as a function of shaft power output for the three fuels is shown in Figure 4-8. The data reveal that NOx emissions decrease as shaft power increases. At an output of 3.5 kWe, all fuel types exhibit a NOx severity index of approximately 1 gNOx/kg. However, due to its higher fuel consumption, NG results in the greatest emissions relative to the energy it delivers, making it less environmentally favourable compared to H_2 and hythane.

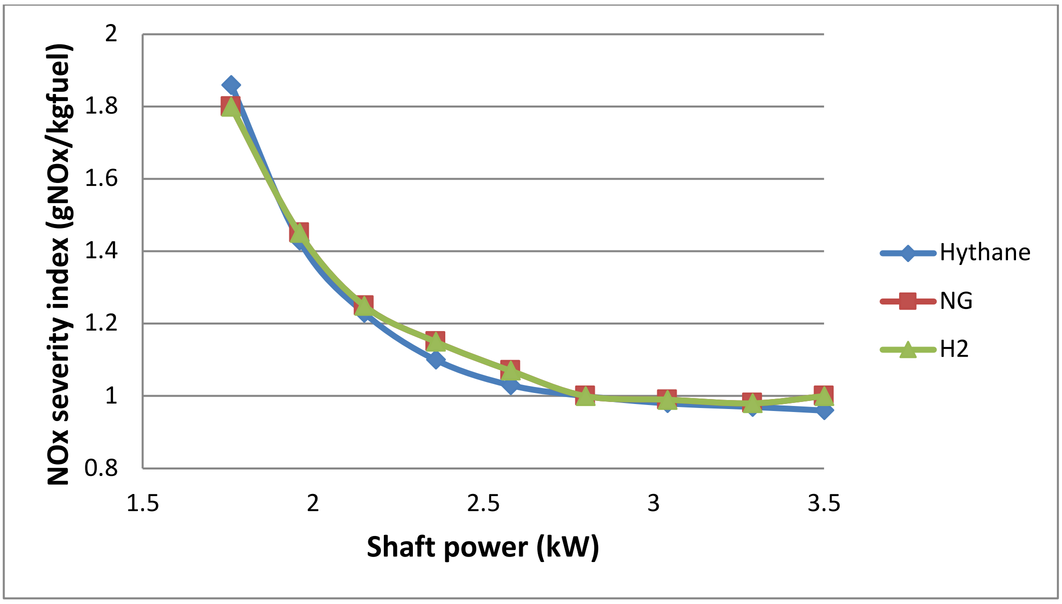

Figure 4-8: Variation of NOx severity index with shaft power delivered for NG, H_2, and hythane

Figure 4-9 compares the heat power output against shaft power for NG, H_2, and hythane. The analysis indicates that the regenerative cycle significantly enhances efficiency across all fuel types, making it a viable and effective strategy for small-scale MGT applications.

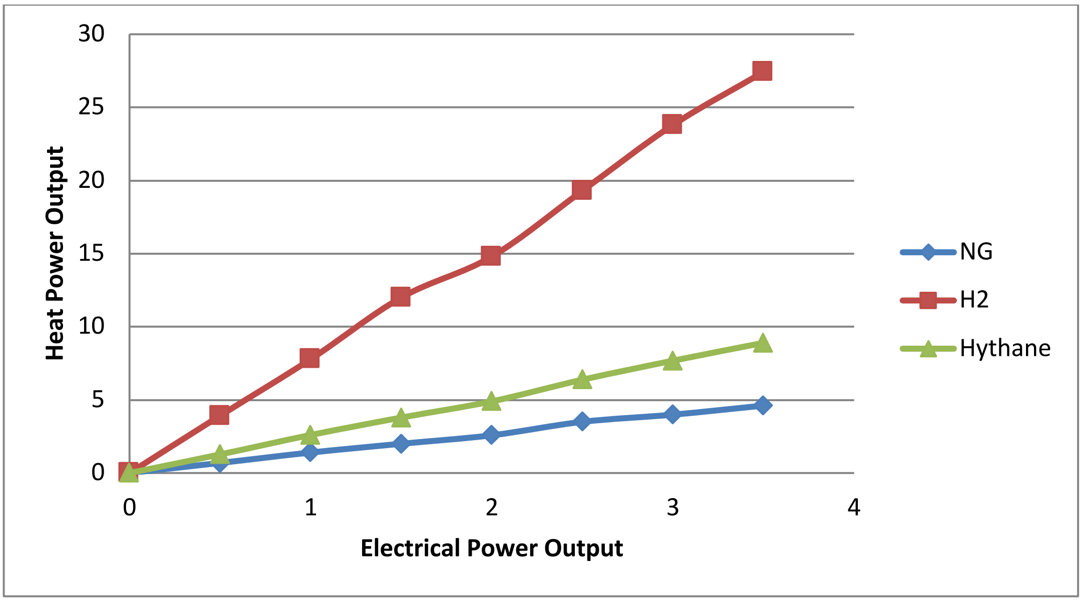

Figure 4-9: Comparison of heat power output with electrical power output for NG, H_2, and hythane

Overall, the simulation results underscore both the benefits and limitations of using NG, H_2, and hythane in MGT. While GasTurb14 provides valuable insights, its core package alone is insufficient for a comprehensive analysis. Additional simulation tools such as MTT Micro-Gas Turbine Lab and GSP Software may be required for more detailed assessments of MGT performance.

2) Aspen Plus

Aspen Plus software was utilised for the process simulation of all fuel types, including NG, H_2, and hythane-powered MGT.

The Peng-Robinson (Ideal) method was employed for this simulation to ensure accurate thermodynamic modelling. The initial process simulation focused on the design cycle of the engine operating with 100% NG as the fuel. The input data, including the inlet properties listed in Table 4-5, were incorporated into Aspen Plus for analysis. The system features two distinct intake sections:

a) Air Intake: Air, primarily composed of 79% nitrogen and 21% oxygen, is drawn into the compressor with a discharge pressure set at 101.325 kPa. As the air undergoes compression, its pressure and temperature rise significantly. The compressed air is then directed to a heat exchanger, where its temperature is further increased. While excess heat is dissipated, the heated air proceeds to the combustion chamber for further utilisation.

b) Fuel Intake: NG is introduced into the combustion chamber at a discharge pressure of 101.325 kPa, matching that of the air intake. Inside the combustion chamber, the compressed air is mixed with NG, and upon ignition, the resulting combustion significantly raises the gas mixture's temperature.

Following combustion, the high-temperature gas expands through the turbine, inducing rotational motion. This rotation generates mechanical work, which is then converted into usable energy. During this expansion phase, the temperature and pressure of the gas mixture drop considerably, facilitating the expansion process. Finally, the exhaust gases are expelled into the atmosphere. This cyclic process, illustrated in Figure 4-10, is continuously repeated to sustain energy production.

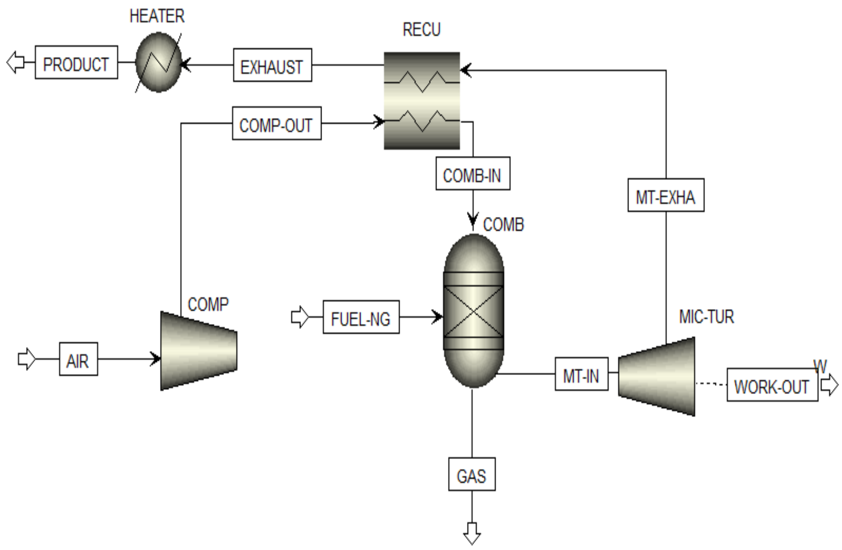

Figure 4-10: The flowchart illustrating the Aspen Plus simulation of the MGT cycle with the fuel of NG

The same process and data were applied to H_2 and hythane in Aspen Plus, incorporating the inlet properties outlined in Table 4-5. The resulting Aspen Plus outlet parameter data for all fuel types is presented in Table 4-7.

Table 4-7: Comparison Output Properties data of Aspen Plus for NG, H_2, and hythane

Properties	NG	H_2	Hythane	Unit
Electric power	3.568	3.501	3.543	kW_e
Combustor Heat	4.610	27.42	8.90	kW
Net stream CO_2 emission	4.21792	0	3.62154	kg/min
NOx severity parameter	0.99954	1.00551	0.99982	-
Fuel Flow rate	$3.6268*10^{-4}$	$1.4814*10^{-4}$	$2.8325*10^{-4}$	Kg/s
PSFC	0.3697	0.1520	0.2236	kg/kW*h

Table 4-8 compares the fuel flow rates, ranging from 0.00035 kg/s to 0.005 kg/s, for all fuel types.

Table 4-8: Comparison of fuel flow rate with electric power output for NG, H_2, and hythane

Fuel Flow Rate (kg/s)	Electric power output (kWe) NG	Electric power output (kWe) H_2	Electric power output (kWe) hythane
0.00035	3.49	8.2	4
0.0005	4.8	12.1	6.2
0.001	11.8	30.2	17
0.0015	17.4	41.2	26
0.002	23	59	32
0.003	30	121.6	42
0.005	51.9	150.9	71.9

Fuel flow rate is a crucial parameter for evaluating the performance of gas turbine fuels. As illustrated in the figure below, at the starting point, a full H_2 MGT delivered 8.2 kWe, compared to 4 kWe for hythane and 3.49 kWe for NG, at a fuel flow rate of 0.00035 kg/s. However, at the endpoint, the full H_2 MGT produced 150.9 kWe, whereas hythane and NG generated 71.9 kWe and 51.9 kWe, respectively, at a fuel flow rate of 0.005 kg/s. Under steady-state conditions, for the same fuel flow rate, the MGT consistently yielded a higher electric power output when fuelled by H_2 compared to NG and hythane. Figure 4-11 illustrates the relationship between fuel flow rate and electric power output across all fuel types.

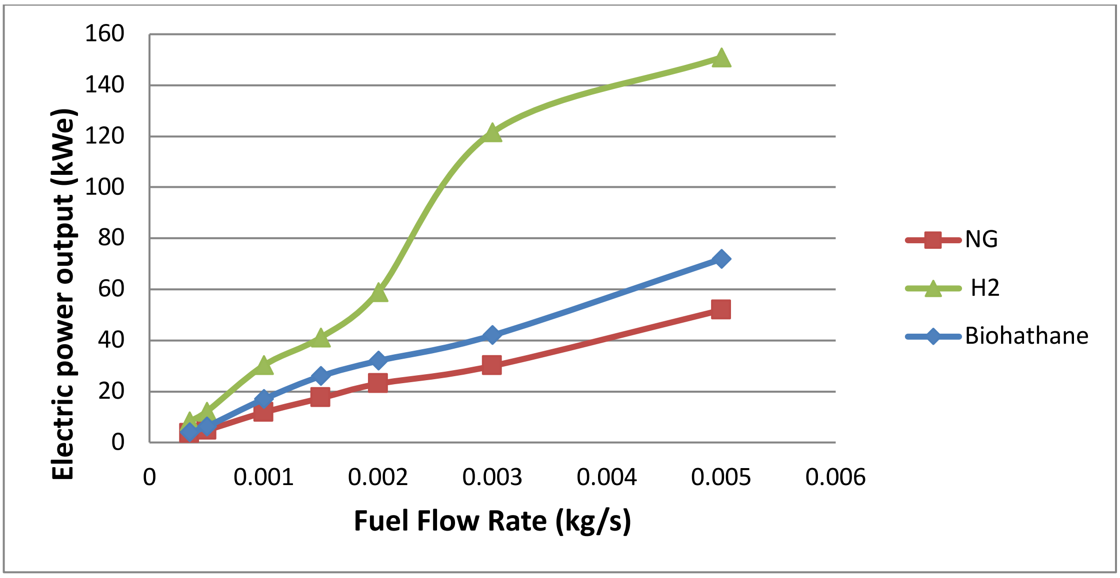

Figure 4-11: Comparison of fuel flow rate with electric power output for NG, H_2, and hythane

As depicted in Figure 4-11, H_2 produces significantly more electric power than NG and hythane at the same fuel flow rate. This indicates that less H_2 is required for energy production, reinforcing its lower pollutant impact compared to NG and hythane while also reducing fuel consumption. Additionally, Figure 4-12 presents the T-S diagram of the MGT operating on NG, H_2, and hythane.

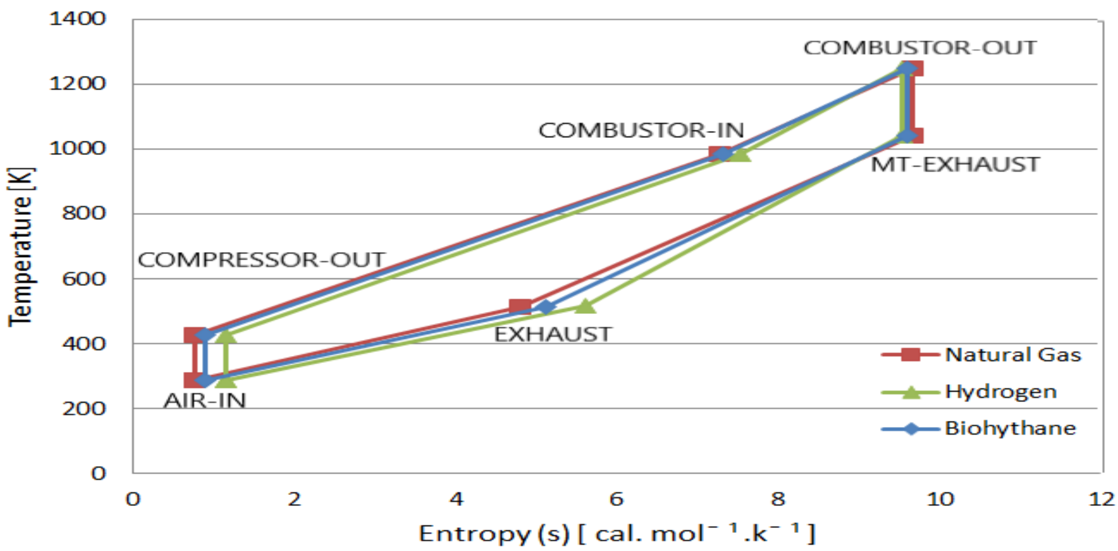

Figure 4-12: T-S diagram illustrating the MGT cycle with NG, H_2, & hythane as fuels

The recuperator effectiveness values, as derived from the graph, are 0.735 for H_2, 0.749 for hythane, and 0.756 for NG. This minor difference in recuperator effectiveness among fuels influences the exhaust temperatures of both the MGT and the overall cycle. The cycle efficiencies recorded for H_2, hythane, and NG were 29%, 27%, and 26%, respectively. The variation in cycle efficiency stems primarily from the energy release in the combustor, where H_2's higher heating density leads to greater overall efficiency compared to hythane and NG.

4.2.3 Discussion

In this research, NG, H_2, and hythane-burnt MGT systems are compared by means of process and performance simulations. Based on the design characteristics of a 3.5 kWe MGT, the system is designed to successfully operate the cycles with these three fuels, and emissions, energy, and exergy analysis of H_2 and hythane are compared to the NG-fired system. The results showed that the incorporation of these renewable fuels significantly improved the performance of the MGT, leading to a notable reduction in gaseous emissions such as CO_2, NOx, and CO.

The result shows that the H_2 combustion in MGT raises the NOx formation, especially when burnt at stoichiometric ratios due to the flame's high temperatures. Maintaining controlled flame temperature levels and designing flameless or non-stoichiometric combustors is key to the development of Hydrogen/hythane systems. The simulation results indicate that producing the same amount of power (i.e., 3.5 kWe), require less H_2 mass flow rate (1.48×10^{-4} kg/sec) as compared to hythane (2.83×10^{-4} kg/sec) and NG (3.63×10^{-4} kg/sec) and therefore lower overall emissions. The GasTurb operation line and the turbo machinery (compressor and turbine) behaviours have received minimal impacts from the fuel switching. This means the combustor design and characteristics are the main limiting component for the transition to H_2-rich gas turbines. H_2 presents the lowest PSFC (Power specific fuel consumption) as compared to hythane and NG fuels due to its high energy capacity and its low fuel density.

Considering the attempts to implement carbon-neutral and renewable fuels in the gas turbine industry by 2030, H_2 and hythane could be preferred fuel options for MGT systems. In this 3.5 KWe MGT, the cycle efficiency for H_2, hythane, and NG was found to be 29%, 27%, and 26%, respectively. Indeed, this core MGT technology can be used in a micro-CHP system to generate base load electricity and fulfil the needs of buildings, similar to conventional household boilers. The installation costs are normally low and if used in combination with heat pumps the system can provide a reliable sustainable solution for future net zero buildings.

4.2.4 Validation

This study validates the MGT with Hythane fuel (this study) by benchmarking its performance against the micro gas turbine (MGT) system from Micro Turbine

Technology (MTT) [231], which Staffordshire University purchased and installed. Both systems operate under nearly identical conditions; however, the Staffordshire MTT unit is designed exclusively for natural gas (NG) operation, while our MGT with Hythane fuel (this study) introduces enhanced fuel flexibility, capable of utilising hydrogen (H_2), hythane (20% H_2 + 80% CH_4), and NG. This flexibility represents a significant advancement toward next-generation MGT-based CHP systems. The Table 4-9 below shows the closely matched operating conditions shared by the MGT with Hythane fuel (this study) and the Staffordshire MTT system, allowing for a meaningful comparison.

Table 4-9: Comparison of Operating Conditions: MGT with Hythane fuel (this study) vs. Staffordshire MTT Systems

Property/Parameter	MGT with Hythane fuel (this study) value	MTT value	Unit
Ambient Pressure	101.325	110	kPa
Ambient Temperature	288.15	313.5	K
Air mass flow rate	0.06	0.053	Kg/s
MGT burner exit temperature	1250	1323.4	K

Validation of both systems has been carried out using NG as the baseline fuel to ensure a fair and industry-standard comparison. Although hydrogen and hythane are increasingly recognised as key alternatives in the energy transition, no existing commercial MGT-based CHP system currently operates on 100% hydrogen or hythane. Therefore, performance predictions for these fuels in our system are extrapolated based on NG results, offering valuable insight into potential future capabilities.

The comparison highlights clear performance improvements of our MGT with Hythane fuel (this study) over the Staffordshire University unit. Specifically, our unit is designed for a higher power output of 3.5 kWe, compared to the 3.2 kWe net electric output of the Staffordshire MTT system, making it better suited to applications requiring enhanced power generation. In terms of electrical efficiency, the Staffordshire MTT system achieves a net electrical efficiency of 16% on NG, whereas MGT with Hythane fuel (this study) demonstrates significantly higher efficiencies: 26% for NG, 27% for hythane, and 29% for hydrogen, underscoring superior energy utilisation even when validated on NG.

While the Staffordshire MTT unit delivers a high CHP efficiency of over 94%, our MGT with Hythane fuel (this study) maintains a strong CHP efficiency above 85%, ensuring robust combined heat and power performance. Furthermore, our system achieves improved thermal management, with a combustor outlet temperature of

976.85°C (1250 K), lower than the Staffordshire MTT system's 1050.25°C (1323.4 K). This reduction indicates improved thermal efficiency and operational stability.

In terms of airflow, the Staffordshire MTT system operates at a mass flow rate of 0.053 kg/s, whereas our system operates at 0.06 kg/s, contributing to its higher power output and greater operational robustness. Additionally, the power-specific fuel consumption (PSFC) of 100% hydrogen in our system is notably lower than that of NG and hythane, thanks to hydrogen's superior energy content and combustion characteristics, which enhance fuel economy. The Figure 4-13 below shows the overall output comparison between the MGT with Hythane fuel (this study) and the MTT system running on NG.

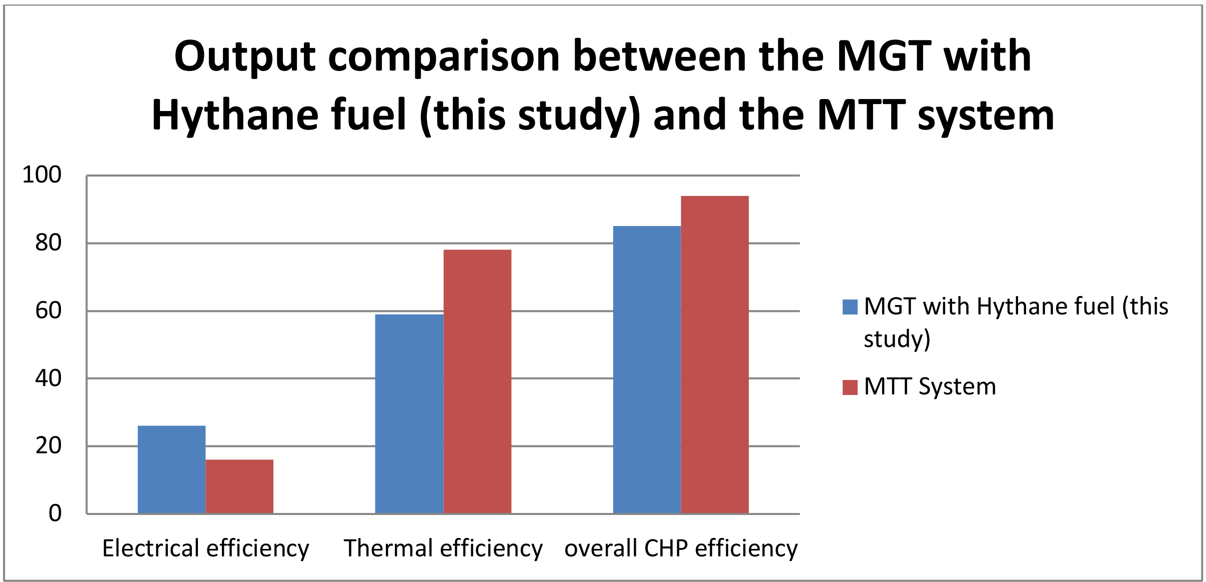

Figure 4-13: Performance Output Analysis of MGT with Hythane fuel (this study) and MTT System

While NG validation remains the cornerstone of this study, the MGT with Hythane fuel (this study) system's capacity to utilise hydrogen-rich fuels aligns with global decarbonisation objectives and energy policies targeting carbon neutrality by 2030. This positions our system as a forward-looking solution, bridging the current reliance on NG with the anticipated transition to low-carbon fuels like hydrogen and hythane.

In conclusion, validation results confirm that our MGT-CHP with Hythane fuel (this study) system not only matches but surpasses the performance of the Staffordshire MTT unit in NG-based operation—delivering higher power output, greater fuel flexibility, improved electrical efficiency, and better alignment with future-ready, low-emission energy targets. This makes it a compelling option for next-generation micro-CHP applications.

4.3 Micro combined heat and power (micro-CHP) systems for household applications: Techno-economic and risk assessment of the main prime movers

This study evaluates four primary micro-CHP technologies—Micro-gas turbines (MGT), Gas engines (GE), Stirling engines (SE), and Fuel cells (FC)—considering on their performance and the technologies and products currently available. Using Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) risk analysis along with Multi-Criteria Decision Analysis (MCDA), the optimal options for residential applications were identified. FC are the most environmentally friendly, offering low emissions but with high costs and slow start-up times. GEs feature well-developed technology, providing fast start-up and high efficiencies, but face challenges with noise and vibration. MGT are becoming more prevalent due to their cost-effectiveness, low maintenance, and quick start-up capabilities. SE offer flexible fuel options, reasonable pricing, and available models, provide a versatile solution. Micro-CHP systems, especially those powered by biofuels and hydrogen, offer great potential for net-zero energy buildings in the future [9].

4.3.1 PESTLE analysis

The **PESTLE** framework offers a comprehensive assessment of the external factors influencing the deployment of a technology (PESTLE). Table 4-10 presents a summary of the key data supporting this analysis.

From a **political** aspect, the focus is on the incentives associated with enacting laws to achieve net-zero emissions, with variations across countries. While the UK has committed to achieving net-zero emissions by 2050, with many sectors advancing their goals to 2030. Several European countries, including Germany and France, support this EU-wide objective, though some Eastern and Central European nations oppose it [328].

The **economic** aspect examines the cost per kilowatt of the unit is examined, though other technical aspects and incentives must also be considered to assess economic feasibility. Depending on the type of technology deployed, unit costs range from £720 to £5217/kWe [98,101,145].

Socially, citizens' willingness to invest in these technologies in different countries is evaluated. Currently, more than 50 micro-scale cogeneration products from over 30 manufacturers (typically under 50 kWe) are identified worldwide. However, the full incorporation of these devices into homes has not been entirely effective due to factors such as slow implementation, underdeveloped technology, and limited awareness. As integration with small-scale CHP systems in tandem with renewable energy grows, these systems are poised to capture a larger share of the residential market [12].

Technical aspect highlights key differences between technologies, including start-up time, efficiency, and performance under part-load conditions, size, power-to-heat ratios, power range, and system reliability. These factors are outlined in Table 4-10.

From a **legal** factor is governed by the micro-generation certification scheme, which mandates that micro-CHP units must have a capacity below 50 kWe or 45 kWth. These units must meet environmental and efficiency standards, act as a substitute for boilers, provide heating year-round, be heat-demand controlled, avoid heat waste, and allow excess electricity to be exported to the grid. Compliance with electrical safety council requirements is also necessary [329].

The **environmental** aspect is concerned with emissions and noise levels. Noise affects household comfort, while particulate emissions are regulated by existing standards. Table 4-10 presents the key data used for PESTLE analysis.

Table 4-10: Summary of prime movers' main characteristics [83][98][101][102][105][109][141][144][145][146][151][163][330]

	Prime Movers	Reciprocating engines	Stirling Engine	Fuel Cell	Micro-gas turbine
	Type of Application	Heating and sanitary water; Future development in trigeneration; Emergency generator	Space heating and sanitary water; Heat storage for longer electrical production	Space heating and sanitary water; High power-to-heat ratio so very valuable for electricity generation	CHP and trigeneration; Widespread monitoring availability, smart-grid frameworks
P	It depends widely on the country. The best is Germany, France, and the United Kingdom				
E	Cost ($/kW)	900-1500 [101]	3700 (£2937) [145]	5000-6500 [98]	1300-2500 [101]
S	The willingness to pay for fuel cells is higher than for the other technologies				
T	Fuel	natural gas, biogas, LPG, sour gas, industrial waste gas, manufactured gas [98]	Any fuel [144]	hydrogen, natural gas, propane, methanol [98]	Natural gas, waste, and sour gases, gasoline, kerosene, diesel, distillate fuel oil [101]
	Size (m^3)	0.77 [98]	0.19 [98]	1.26 [98]	0.63 [98]
	Overall CHP Efficiency	86.7-94.9 [83,141]	90-96 [105,109]	88 - >95 [151,163]	80 - >94 [98,330]
	Power-to-heat ratio	0.5-1.2 [98]	0.1-0.4 [98]	1-2 [98]	0.5-0.7 [98]
	Part Load	Good [101]	Good [144]	Good [98]	Satisfied [101]
	Availability	96-98 [98]	99% [98]	99% [98]	98-99% [98]
	Start-up Time	10 s [98]	20 min – 1 hr [146]	3 h-2 days [98]	60 s [98]
L	micro-CHP unit must be below 50 kWe or 45 kWth; the main heating system; act as a boiler substitute; must display better environmental benefits and efficiency; provide heating service throughout the year; be controlled by heat demand; never waste heat and electricity--if produced in excess, can be exported to the grid.				
E	Noise	High [101]	Low [144]	Low [146]	Moderate [101]
	NO_x (kg/MWhe)	0.99 [102]	0.63 [102]	0.011-0.016 [98]	0.14-0.49 [98]
	CO_2 (lb/MWhe)	650 [101]	999.72 [98]	980-998 [145]	720 [101]
	Comments	Significant heat recovery potential (around 60%); low output temperatures	Easy installation: Thermal storage could significantly enhance its electric energy delivery	Good power quality, catalyst could be expensive and highly sensitive to impurities	Compressor is required. This appliance could vary its yield depending on ambient conditions.

4.3.2 MCDA analysis

A MCDA is a quantitative method that considers both technical and non-technical factors to determine the most suitable choice among multiple alternatives. Given the complexity of micro-CHP technology, an MCDA was conducted to evaluate various options. This analysis helped identify the most appropriate solution for domestic applications. The first step was to establish the criteria for evaluating the appropriateness of the four systems. To ensure account for all relevant elements, a PESTLE risk analysis was conducted for each technology. The selected criteria are listed in Table 4-11.

Table 4-11: Criteria used to perform the MCDA

Ranking	Criteria	Definition
1	Price (£/kW)	Price of the unit and installation
2	Overall efficiency (%)	The higher the efficiency, the higher energy amount is produced with the same quantity of fuel
3	Power-to-heat ratio	A high P/heat infers that more electricity is sent to the grid (or less is imported) so it is economically attractive (if incentives are available)
4	Noise	Low noise is required for the comfort of the residents
4	Size of the unit (m^3)	The unit must be not too cumbersome to fit in the house
5	Willingness to pay (WTP)	The higher the WTP, the more willingly people accept the technology
5	NO_x (kg/MWh)	The emissions must be below to not impact on residents' health and the environment.
5	VOC (kg/MWh)	
5	CO (kg/MWh)	
5	CO_2 (kg/MWh)	
6	Power range (kW)	The technology must be able to meet the low domestic demand (about 1 KWe)
7	Part-load performance	Part-load performance is important to avoid losses of energy due to over-production
8	Start-up time	Domestic demand can vary quickly, the system must respond rapidly
8	Availability	Availability characterizes the maintenance needed on the unit; if the availability is high the unit can work longer and the cost for maintenance would be lower.

After defining all the criteria, they were prioritised based on their importance. The criteria related to price and economic benefits (such as the unit and installation cost, overall system efficiency, and power-to-heat ratio) were considered the most important. These were followed by environmental criteria (such as emissions, noise levels, and appliance size), and finally, operational factors (including power capacity, performance under partial load, start-up duration, and system availability). The Decerns MCDA software was utilised to assign weights to each criterion. Then, based on the results of the PESTLE risk analysis, each technology was rated on a scale from 1 to 10 for each criterion. The scores were multiplied by the respective weight of each criterion and summed to determine the final results for each technology.

4.3.3 Results

The outcomes of the MCDA analysis provided a clear indication of the most appropriate technology for single-household applications, based on comparative scores across various criteria illustrated in Figure 4-14 [9].

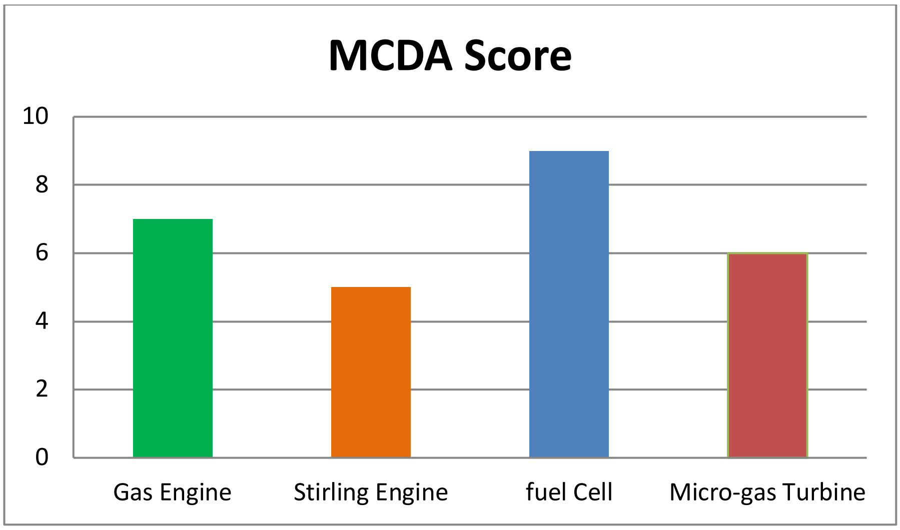

Figure 4-14: MCDA results for various prime movers in micro-CHP Systems [9].

Considering all the criteria, Fuel cells emerge as a top contender for residential use. They offer excellent environmental performance (low noise and emissions), strong technical attributes (high efficiency, reliability, and part-load capabilities), and considerable consumer acceptance. Although its high price is a challenge, it is mitigated by incentives for electricity production. However, while Germany and the UK offer generous incentives, countries like France and Belgium provide moderate incentives, and many other European nations have lower support. In areas where the power-to-heat ratio holds less value, Stirling engines achieve nearly the same score as fuel cells when this criterion is omitted from the evaluation. To increase adoption, fuel cells need further cost reductions, as their high price remains a key obstacle [9].

The Stirling engine, while receiving the lowest MCDA score in this study, presents a promise for residential use due to its high heat output, quiet operation, competitive pricing, and compact size, making it ideal. To become more attractive, its environmental features, as well as its operational flexibility (e.g., start-up time and part-load operation), need improvement. Gas engines ranked as the second most viable choice, benefiting from high availability, quick start-up, and strong part-load performance, they are well-suited for emergency applications in hospitals, retirement homes, and larger residences. The micro-gas turbine, although still an emerging option for residential applications, shows potential as the most cost-effective choice, delivering good overall efficiency. Future research is needed to adjust the power output of micro-gas turbines to meet residential market demands, improve their electrical efficiency, enhance operational flexibility, and control emissions (both noise and gases), which could make them a competitive option [9].

Figure 4-15 highlights the strengths and weaknesses of each micro-CHP technology based on MCDA results. Due to significant variations in data values, a feature scaling technique was employed to normalise them, assigning values on a 0-10 scale, enabling the construction of radial plots in Figure 4-15, where higher values indicate better performance for a given criterion. For example, while gas engines exhibit high overall efficiency suitable for household applications, fuel cell technology remains less favourable due to its cost.

According to the MCDA evaluation, fuel cells achieve the highest overall score for domestic use, primarily attributed to their strong environmental advantages, low noise levels, high part-load efficiency, and optimal heat-to-power ratio. Gas engines, despite achieving the highest electrical efficiency (approximately 40%), face challenges related to noise and vibration. Stirling engines, known for their technological maturity and fuel flexibility, lag behind in electrical output and effective heat recovery. Micro-gas turbines, as a relatively new entrant in the micro-CHP market, receive moderate scores across all criteria but perform better overall than Stirling engine-based systems. These turbines offer reliability, cost-effectiveness, and fuel flexibility while operating continuously for extended periods with limited maintenance requirements [9].

Figure 4-15: Features of each prime mover based on the MCDA analysis [83,98,101,102,105,109,141,144–146,151,163]

4.3.4 Discussion

This study provides an independent evaluation of various micro-CHP technologies, including gas engines, Stirling engines, fuel cells, and micro-gas turbines. By analysing the strengths and limitations of these technologies, the research offers a comprehensive assessment of the current advancements in micro-CHP systems and the commercially viable options for residential use. A risk assessment of these technologies was conducted using PESTLE analysis, while an MCDA approach was employed to determine the most suitable technologies for household applications.

Gas engines stand out for their quick start-up capabilities, high electrical efficiency, and well-established technological maturity. Stirling engines, already available in the market, offer quiet operation, compact sizing suitable for residential properties, and a broad selection of products; however, enhancing their electrical efficiency remains a key area for improvement. Micro-gas turbines are gaining attention due to their affordability, small footprint, minimal maintenance requirements, and capability to integrate carbon capture and storage (CCS) technologies while utilising carbon-neutral fuels such as biogas and hydrogen. Fuel cells, on the other hand, are highlighted for their exceptionally low emissions and noise levels. While the high cost of fuel cell systems poses a challenge, this may be offset by their superior power-to-heat ratio and strong operational availability, enabling surplus electricity to be fed into the grid in countries offering financial incentives, such as Germany and the UK. However, fuel cells have a relatively long start-up time and require continuous operation for optimal performance.

Micro-gas turbines offer a competitive cost per kilowatt, shorter start-up time compared to fuel cells, and lower emissions than gas engines. They exhibit acceptable noise levels, high fuel adaptability, and ease of maintenance. However, their limited power range for residential applications remains a challenge, requiring further development by manufacturers to better suit the household energy market. When considering fuel versatility and emission control, Stirling engines and micro-gas turbines demonstrate greater tolerance for unconventional fuels, while fuel cells and gas engines are more susceptible to fuel impurities. Moreover, advancements in grid integration and micro-grid development could enhance system reliability and energy security in remote locations.

The MCDA analysis reveals that fuel cells rank highest for domestic use due to their environmental benefits, though their widespread adoption depends on reducing costs through technological advancements. Gas engines secure second place owing to their reliability and technological maturity, yet challenges such as noise levels and the availability of smaller-capacity units (1–5 kWe) must be addressed by manufacturers. As an emerging micro-CHP technology, micro-gas turbines rank third, offering a balanced performance across multiple criteria. Stirling engines, while benefiting from affordability, product availability, and fuel flexibility, require enhancements in electrical efficiency to remain competitive. Micro-CHP systems are capable of reaching electrical efficiencies as high as 40%, with total combined heat and power efficiencies exceeding 90%. When integrated with renewable energy sources and fuelled by biofuels or hydrogen, micro-CHP systems present a viable solution for delivering clean, reliable, and decentralised energy to households, supporting the transition toward net-zero buildings.

5. CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter provides a comprehensive summary of the conclusions drawn from the project and outlines valuable recommendations for future studies. Building on the analysis and findings, areas of improvement and potential directions for further exploration are highlighted. These suggestions are intended to support the advancement of more efficient and sustainable systems in future work, focusing on both technological innovations and real-world applications. To overcome existing obstacles and refine approaches, additional research is essential to enhance system performance and minimise environmental impact.

5.1 Conclusion

This research has undertaken a comprehensive investigation of micro-combined heat and power (micro-CHP) systems, with a specific focus on performance characteristics, fuel flexibility, and techno-economic feasibility for residential applications. By integrating an extensive literature review with detailed performance simulations and comparative evaluations, the study successfully fulfilled its core aims and objectives, offering valuable insights into the future potential of decentralised energy generation.

The research commenced with a structured exploration of the foundational elements of the study, including its background, motivation, research questions, objectives, and inherent limitations. This conceptual framework established a clear direction for the investigation. The literature review was categorised into four major thematic areas: micro-CHP technologies, prime mover technologies, the role of biomass and biofuels as sustainable energy sources, and the technical challenges and opportunities associated with hydrogen and hythane-fuelled systems. This critical analysis helped identify key research gaps and avenues for future innovation in the micro-CHP domain.

Central to this study was the application of simulation tools—Aspen Plus and GasTurb—to model and evaluate micro-CHP system performance. The analysis included two case studies: a 5.5 kW micro-gas turbine (MGT)-based CHP system integrated with a PEM electrolyser and fuel cell unit, and a standalone 3.5 kWe MGT system tailored for residential use.

In the 5.5 kW MGT-CHP configuration, pure hydrogen fuel produced the highest heat output (39.4 kW) owing to its superior adiabatic flame temperature but exhibited a slightly reduced electrical output (5.03 kW) due to its lower density. In comparison, natural gas (NG) and methane (CH_4) delivered higher electrical outputs (5.73 kW) but significantly lower thermal outputs (~7.4–7.5 kW), indicating a better electrical conversion efficiency. Hythane (80% CH_4 + 20% H_2) emerged as a balanced transitional fuel, offering a thermal output of 13.9 kW and an electrical output of 5.53 kW, while reducing CO_2 emissions to 3.1 kg/h from 5 kg/h (as in NG and CH_4). Hydrogen combustion resulted in zero CO_2 emissions but elevated NOx levels (0.095 kg/h), necessitating advanced emission control strategies such as steam dilution or flameless combustion. Notably, the system achieved an overall CHP efficiency of 96% and an electrolysis efficiency of 82%, surpassing benchmark systems like the MTT-based MGT-CHP at Staffordshire University (combined efficiency >94%, 3 kW output), demonstrating its suitability for high-demand domestic applications.

In the 3.5 kWe MGT system, hydrogen again exhibited superior fuel efficiency and environmental performance, recording the lowest power-specific fuel consumption (PSFC) at 0.1520 kg/kWh, followed by hythane (0.2236 kg/kWh) and NG (0.3697 kg/kWh). This performance stems from hydrogen's high heating value and lower required mass flow rate (1.48×10^{-4} kg/s vs. 2.83×10^{-4} and 3.63×10^{-4} kg/s for hythane and NG, respectively) for the same power output. Hydrogen also eliminated CO_2 emissions, making it the most environmentally favourable option. Although NOx severity was slightly elevated (1.00551), this can be mitigated through advanced combustor designs. Hythane showed promise as a transitional fuel, reducing CO_2 emissions (3.62 kg/min) and achieving improved PSFC relative to NG. Efficiency-wise, hydrogen led with 29%, followed by hythane (27%) and NG (26%), with minor deviations attributed to recuperator performance and combustion characteristics. At a fixed fuel flow rate (0.00035 kg/s), hydrogen delivered the highest power output (8.2 kWe), far surpassing NG (3.49 kWe) and hythane (4.0 kWe). These results reaffirm hydrogen's potential in small-scale, low-emission, high-efficiency energy systems, particularly when paired with domestic heat pumps and renewables for net-zero buildings by 2030.

The study confirmed the high fuel flexibility of micro-CHP systems and demonstrated that the integration of a recuperator enhances overall efficiency by enabling lean combustion. Systems powered by hydrogen and hythane achieved combined efficiencies of up to 96%, reflecting strong potential for residential applications.

Furthermore, the comparative assessment of prime mover technologies—including MGTs, gas engines, Stirling engines, and fuel cells—revealed diverse operational profiles. Fuel cells were found to be the most sustainable, though they incur higher costs and extended start-up times. Gas engines offer high efficiency and rapid response but face limitations from vibration and acoustic noise. MGTs stood out for their low maintenance needs, compactness, and stable operation. Stirling engines provided excellent fuel flexibility and affordability, making them strong contenders for domestic-scale systems.

Additionally, the study evaluated the feasibility of carbon-neutral and renewable fuels, particularly hythane, which demonstrated high efficiency and reduced emissions across multiple scenarios. The incorporation of PESTLE and MCDA frameworks provided a holistic approach to selecting suitable prime mover technologies by accounting for technical, economic, environmental, and socio-political factors.

In conclusion, this research underscores the strategic role of micro-CHP systems in the evolving energy landscape, especially in the context of net-zero building targets. It advocates for the continued development of hydrogen production (e.g., via anaerobic fermentation) and infrastructure to improve fuel availability and reduce costs. Future work should prioritise experimental validation through pilot-scale demonstrations and explore policy instruments that support the broader deployment of micro-CHP systems. Addressing these challenges will enable micro-CHP to significantly enhance residential energy efficiency, reduce carbon emissions, and contribute to a more resilient, decentralised energy infrastructure.

5.2 Recommendations for future work

The study highlights several key recommendations for optimising micro-gas turbine (MGT) and fuel cell (FC) systems in micro-combined heat and power (micro-CHP) applications. For MGT systems, transitioning to hydrogen (H_2) and hythane (H_2 + CH_4) as fuel sources is recommended to reduce CO_2 emissions and improve combustion efficiency. By integrating renewable energy sources such as solar or wind power with the system, hydrogen production can be enhanced, leading to a more sustainable and cost-effective operation. Additionally, increasing the size of the

MGT-CHP combustor when operating with H_2 or hythane is suggested to improve the reactant residence time, ensuring stable combustion within the combustor and preventing flame blowout. Maintaining controlled flame temperatures and adopting non-stoichiometric or flameless combustion techniques is crucial for minimising NOx emissions when using hydrogen-rich fuels.

Furthermore, the efficiency of MGT systems is shown to be fuel-dependent, with H_2 achieving the highest efficiency (29%), followed by hythane (27%) and natural gas (26%). The research indicates that minimal modifications to the compressor and turbine are needed when transitioning to hydrogen-rich fuels, with combustor design being the primary limiting factor. Given the push toward carbon-neutral technologies by 2030, adopting H_2 and hythane in MGT systems presents a viable pathway for sustainable energy production. Additionally, the implementation of carbon capture and storage (CCS) technologies alongside MGT systems can further enhance their environmental performance.

For fuel cells, their low emissions, high power-to-heat ratio, and efficiency make them an attractive option for micro-CHP systems, particularly in domestic applications where incentives for grid electricity sales exist. Despite their high initial cost and longer start up time, fuel cells offer significant advantages in reducing greenhouse gas emissions and providing reliable power. Integrating fuel cells with renewable energy sources and micro-grid systems can enhance energy security and sustainability. However, advancements in reducing system costs and improving fuel impurity tolerance are necessary for broader commercial adoption.

Overall, both MGT and FC technologies have promising applications in decentralised energy systems, particularly when coupled with renewable energy sources and carbon-neutral fuels. MGT offer lower costs and quicker start up times, making them a practical solution for domestic and small-scale industrial applications, while fuel cells provide superior environmental benefits and higher efficiency, albeit at a higher cost. Future research should focus on improving combustor designs for hydrogen combustion in MGT, enhancing the cost-effectiveness of fuel cells, and exploring hybrid systems that leverage the strengths of both technologies for optimal energy efficiency and sustainability.

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APPENDICES

Published Paper 1

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Micro Combined Heat and Power (micro-CHP) Systems for Household Applications: Techno-economic and Risk Assessment of The Main Prime Movers

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ABSTRACT

To limit global warming and meet international environmental targets, more environmentally benign technologies must be used in the residential market. Combined Heat and Power (CHP) at the micro-scale (<50 kWe) is seen as one of the best solutions that offers simultaneous generation of both electricity and heat with high overall efficiencies using environmentally friendly fuels (e.g., biofuel, hydrogen, syngas). In this study, four major micro-CHP prime movers (i.e. Micro-gas turbine, Gas engine, Stirling engine, and Fuel cell) have been evaluated in terms of their performance and the currently available technologies and products. The most suitable options for household applications were identified using Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) risk analysis and a Multi-Criteria Decision Analysis (MCDA). Fuel cells display the best environmentally friendly properties despite their price and high start-up time. Gas engines (Reciprocating engines) have the most developed technology with the fastest start-up time and high efficiencies but have vibration and noise issues. Micro-gas turbine micro-CHPs are emerging into the market with relatively cheaper prices, lower maintenance, and good start-up time. Stirling engines are fuel flexible with reasonable prices and available products. Micro-CHP systems, particularly when running on biofuels and hydrogen, provide excellent energy solutions for the future net zero buildings.

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1. Introduction

Access to clean and affordable energy has become one of the most strategic need of the countries, but the supply of energy has become one of the most pressing concerns in the world. On the one hand, looking at the depleting status of the sources of fossil energy and the detrimental effects of burning these types of fuel on the environment determine the necessity and importance of utilizing renewable energy sources and optimizing energy convertion of fossil fuels. One of the most important forms of energy is electricity, which has a great impact on the energy basket of every country. Currently a large amount of electricity worldwide is generated through the conversion of fossil fuels. Therefore, due to the limitation of the resources of fossil fuel, the controlling issue of energy costs, energy consumption on the environment, reducing the effects of conversion, improving the efficiency of heat and power generation, and reducing the waste are of high importance (Fan et al. 2020).

The generation of electricity coupled with the use of generated heat is a rapidly developing method that reduces overall losses and increases efficiency. This method is generally known as the Combined Heat and Power (CHP) generation. CHP technologies are now widely used, and this technology has reduced environmental emissions. CHP technology can potentially improve the energy supply system and the energy supply security and reliability. The CHP system produces both heat and electricity together from a single source of fuel (Fan et al. 2020). The technology of the combined heat and power (CHP) system can recover waste heat from electricity production to generate hot water, space heating, and more specific steam or heat utilized for industrial processes (Evaluation of combined heat and power technologies 2022). Heat is the main output of a micro-CHP system, with some generation of electricity as by product, at a typical ratio of about 6:1 for domestic appliances (Martinez et al. 2017). Figure 1 shows the overall energy efficiencies in a conventional power and heat supply vs. micro-CHP system for a house with 3KWe and 15 KWth energy requirements.

CHP can reduce up to 30% of carbon emissions compared to the separate generation of electricity and heat through an electrical power station (grid) and a gas-fired boiler. Where the demand for both electricity and heat exists in the same place, combined heat and power (CHP) can reduce the cost of energy by up to 40%, and its payback period is 1–3 years (Centrica Business Solutions 2018). However, the improvements in CHP technology over time have resulted in properly designed CHP systems typically operating with an overall efficiency of 65% to 85%, with some of the systems approaching 90%. This is compared to the overall efficiency of only 45% to 55% when the thermal and electrical energy are provided separately (Kelly, McManus, and Hammond 2014).

The total system efficiency (ηo) of a CHP system is the sum of the net useful electric output (W_e) and net useful thermal output (ΣQ_{th}) divided by the total fuel energy input (Q_{fuel}), as shown below:

$$\eta_0 = (W_e + \sum Q_{th})/Q_{fuel} \quad (1)$$

Calculation of the total system efficiency evaluates the output of combined CHP (i.e., useful thermal and electricity output) based on the consumption of the fuel (Combined heat and

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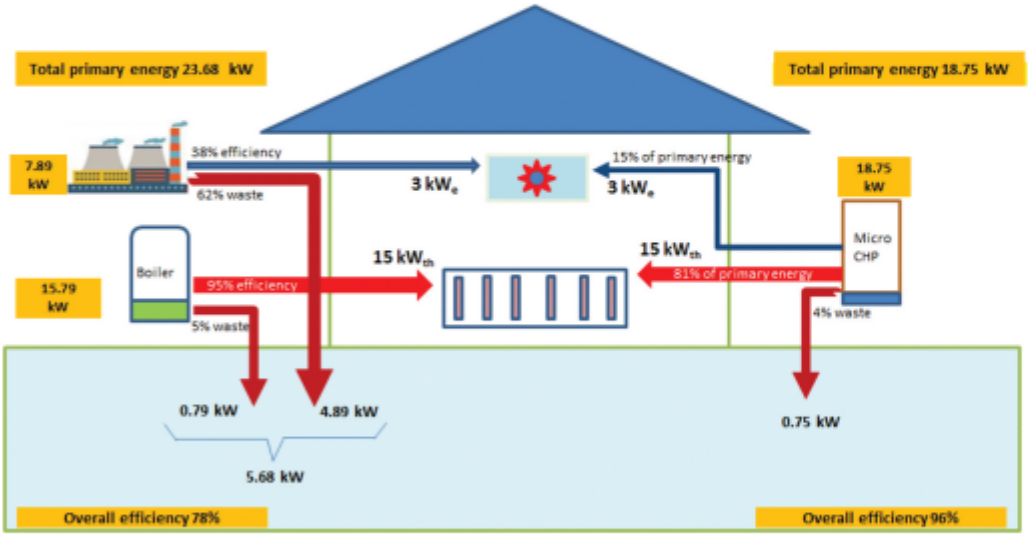

Figure 1. Conventional power and heat vs micro-combined heat and power generation, adapted from Progressing towards low carbon technologies for domestic use (Oakey and Gohari Darabkhani 2015).

power (CHP) Partnership, Methods 2022). The overall CHP efficiency is high and higher efficiency can effectively reduce the emissions of NOx, greenhouse gas emissions, SOx, and volatile organic compounds as well (Ferraina 2014).

CHP technology can be categorized in terms of their different sizes, i.e., the capacity of installed electricity. Installations with greater than 1 MWe of an installed capacity are considered to be large-scale CHP (Ferraina 2014). They represent 94.1% of the total CHP worldwide installed capacity and are used mainly in industrial sites (Points 2019). Sizes between 50 kWe to 1 MWe of CHP units are considered small-scale CHP (Ferraina 2014) while below 50 kW of CHP units are considered a micro-scale CHP system. Although large-scale CHP systems have been available for many years for commercial use, micro-CHP with an electrical power of <50 kW are relatively new systems, generating low cost and low carbon electricity and heat for homes and domestic applications (Microgeneration Certification Scheme WG 8 2012). The main overview of this review paper is to conduct a performance analysis for prime movers at small scales for decentralized power generation. First, the available technological development for micro-CHP will be reviewed. Afterward, the PESTLE and MCDA methodology will be applied to identify the best option among the prime movers for domestic applications.

2. Prime movers

2.1. Micro-gas turbines

Micro-gas turbine (MGT) is an advanced technology with a fast load response and a simple structure. MGT is one of the best options for the next generation of distributed power systems, where fossil fuels will be replaced largely with renewable energies (Olsson et al. 2021; Xiao et al. 2021). In the last decades, the development of micro-gas turbinesystems boosted due to their small size, low noise, cost competitiveness, low carbon emissions, and flexibility for operations. Besides this, the application of micro-gas turbine (MGT) is more flexible and broader with multi-fuel capacities (Guan et al. 2021). In today's market, micro-gas turbines are available in different sizes and cover a large range of power outputs (Aslanidou et al. 2021). In 2021, the global market size of micro-gas turbines was US$ 61.85 million, and now it is expected to be worth US$ 139.6 million by 2030. Figure 2 shows the micro-gas turbine market size from 2021 to 2030 in USD Millions (Data Bridge Market Research 2022).

The electrical efficiency of MGT is still not good (between 15% to 25%), but it can improve if recuperated systems used. The thermal efficiency however is normally more than 70% which is most suited for small-scale applications (Olsson et al. 2021). The overall combined heat and power efficiency of these systems can go above 94%. Micro-gas turbine (MGT) systems can also be combined with other energy utilization equipment or recycling system, such as solid oxide fuel cells, Organic Rankine cycle, etc. (Guan et al. 2021). MGT has several important components which are Turbine, Combustor, Compressor, Electricity generator, and Recuperator (Olsson et al. 2021). Figure 3 shows the schematics of a recuperated micro-gas turbine engine.

Table 1 shows a list of commercially available MGT Micro-CHP systems with a power range of less than 50 kWe with their characteristics.

The advantages and disadvantages of micro-gas turbines are presented in Table 2.

2.2. Reciprocating gas engines

Reciprocating or piston engines are a well-established and widely used technology to generate power for several

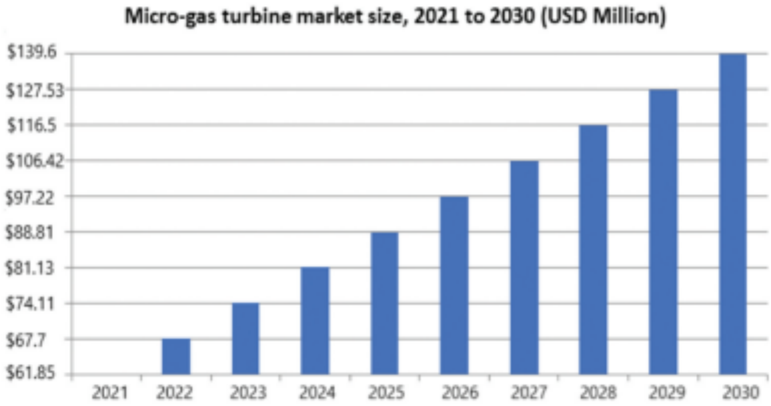

Figure 2. Micro-gas turbine market size, 2021 to 2030 (USD million), adapted from (Micro, Heat, and PCHP n.d.).

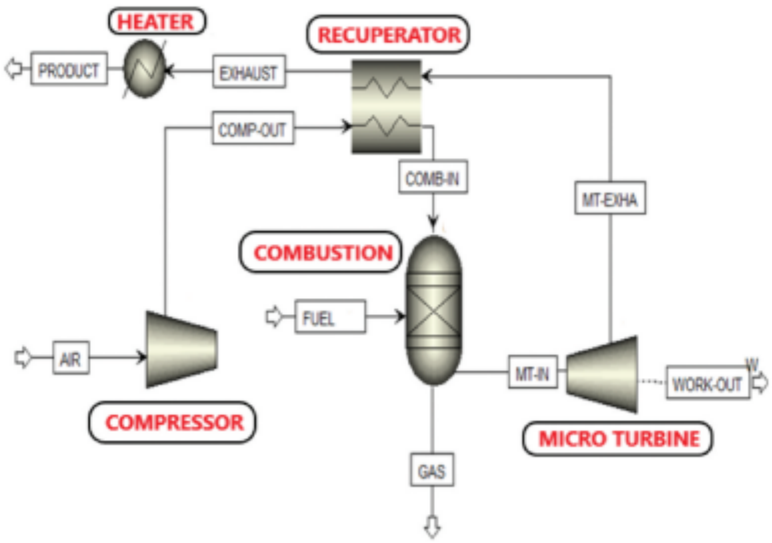

Figure 3. Schematics of micro-gas turbine engine (EPA 2017; Olsson et al. 2021).

Table 1. Micro-gas turbine micro-CHP systems in the market.

Brand	Model	Electrical output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Noise (dB)	Dimensions (H × W × D) (mm)
MTT (EnerTwin 2020)	Enertwin	3.2	16	>94	55	995 × 600 × 1,170
Capstone (Pure World Energy 2020)	C30	30	26	90	<60 bB	1,800 × 760 × 1,500

applications including industrial and residential applications mainly in CHP systems. Reciprocating engines have good part-load efficiencies, start quickly, have generally high reliabilities, and follow the required load well. Reciprocating engines have two main types: one is Spark ignition engines, and the other one is Compression ignition or diesel engines (Freng, Turan, and Ther- 2019). Reciprocating engines are all characterized to create a heat engine by the use of a piston reciprocating in a cylinder that can produce electricity or power (Breeze 2018). A reciprocating cogeneration gas engine is a reciprocating engine that drives a power generator to generate electricity and uses the produced waste heat to meet the demand for thermal energy. That type of heat comes from the hot exhaust gases and the cooling water of the engine (Campos Celador et al. 2011). Figure 4 shows a schematic of the reciprocating engine of a micro-CHP system.

Table 2. Micro-gas turbine advantages and disadvantages (EnerTwin 2020; EPA 2017; Houssein, Fardoun, and Louahlia 2017; Kaparaju and Rintala 2013; What are the different types of cogeneration prime movers? 2023; Zheng et al. 2021).

Advantages	Disadvantages
Fast start-up (around 60 s).	Gas fuel is high pressure (MGT typically requires 3–5 bar fuel supply pressure).
Low weight per unit power and compact size (weight empty is around 205 kg and weight with water and oil is around 215 kg).	The electrical efficiency is low.
A very reliable and low number of moving parts (it contains only one moving part).	The relative capital costs related to this prime mover are high (1300–2500 $/kW).
Emissions level is low. NOx (kg/MWhe) = 0.14–0.49 NOx 9-37 ppm @ 15% O_2 CO_2 (kg/MWhe) = 327 CO 40-80 ppm @15% O_2	Requires high-speed bearings/generators and limitations on continuous on/off operations.

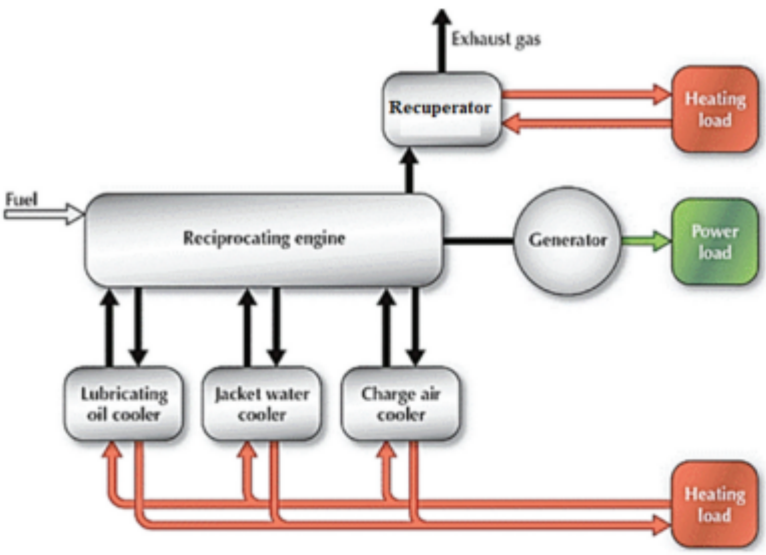

Figure 4. Schematic of reciprocating engine heat and power system (Apunda and Nyangoye 2017).

Table 3. Reciprocating engines in commercially available micro-CHP systems and their characteristics.

Brand	Model	Fuel	Electrical output (kW)	Thermal output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Noise (dB)	Dimensions (mm) (W × D × H)
Dachs (Senertec 2021)	G 5.5	Natural gas	5.5	14.8	25.6/28.4	93.9/104.2	48	720 × 1,070 × 1,270
Dachs (Senertec 2021)	F 5.5	LPG	5.5	13.8	26.8/29.1	93.8/101.9	47	720 × 1,070 × 1,270
Bosch (Bosch n.d.)	CHP CE 12 NA	Natural gas	6–12	13.75–27.5	30.2	-	56	882 × 1,600 × 1,263
Bosch (Bosch n.d.)	CHP CE 19 NA	Natural gas	9.5–19	18–36	34	-	56	900x1,800x1,010
Bosch (Bosch n.d.)	CHP CE 50 NA	Natural gas	25–50	40–80	33.8	87.9	65	960x2,930x1,730
Bosch (Bosch n.d.)	CHP CE 70 NA	Natural gas	35–70	54.5–109	34.3	87.7	68	960x3,275x1,730
EC POWER (Ec Power 2016)	XRGI 6	Gas (all qualities), propane, butane	6	12.4	30.1	92.4	49	640x930x960
EC POWER (Ec Power 2016)	XRGI 9	Gas (all qualities), propane, butane	9	2.1	29.3	94.9	49	640x930x960
EC POWER (Ec Power 2016)	XRGI 15	Gas (all qualities), propane, butane	14.5	36.7	29.3	-	53	750x1,120x1,170
EC POWER (Ec Power 2016)	XRGI 20	Gas (all qualities), propane, butane	20	44.7	32.7	-	49	750x1,120x1,170
EC POWER (Ec Power 2016)	XRGI 25	Gas (all qualities), propane, butane	24	48	31	93	-	750x1,120x1,170
SokraTherm (Sokra Therm 2020)	FG 34	Sewage gas/Biogas	35	65	31.3	89.3	62	900x2,200x1,830
EAW (EAW 2014)	BHKWTypEWK10S	Gasoline	10	19	30.4	87.2	-	770x1,600x2,000
Viallant (Build Up 2012)	Ecopower1.0	Natural gas	1	2.5	26.3	92	-	-

Table 4. Reciprocating engines: advantages and disadvantages (EPA 2017).

Advantages	Disadvantages
Fast start-up	Maintenance cost is high.
Power efficiency is high with part-load operational flexibility.	Limited to lower temperature cogeneration applications.
The investment cost is relatively low.	Relatively air emissions are high.
Has good load-following capability.	High levels of low-frequency noise.
Can be overhauled on the site with normal operators.	Must be cooled even if recovered heat is not used.
It operates on low-pressure gas as well.	The high number of moving parts, and might need substantial foundations.

Table 3 shows a list of commercially available reciprocating engines with their characteristics.

The advantages and disadvantages of reciprocating engines are presented in Table 4.

2.3. Stirling engine

The Stirling engine is a type of external combustion engine. Stirling engines (SE) offer high heat sink temperatures and a good part load performance which makes them a good and a suitable candidate to serve as a prime mover in micro-combined heating and power applications (Lavelle 2012; Udeh et al. 2021). The Stirling engine appears as an emerging technology for single-family and small multi-family houses. It can provide all those basic and essential benefits of the micro-CHP system, but also those attributable to the Stirling technology itself, such as low emissions and multi-fuel capability, both from the pollutant and acoustic points of view (González-Pino et al. 2020). Figure 5 shows a Stirling engine-based micro-CHP unit.

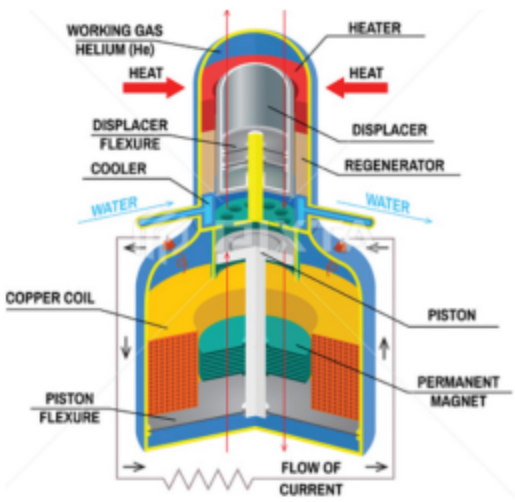

Figure 5. Stirling engine of micro-CHP system (Stirling engine generator diagram 2023b).

Table 5 shows a list of commercially available Stirling engines and their characteristics. Higher economic cost of the engine.

2.4. Fuel cell

A fuel cell is a promising technology with its best record of safety, sustainability, and environmental benefits. Fuel cells have several different types: proton exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), and alkaline fuel cell (AFC). For the applications of combined heat and power systems (CHP) generally, heat is obtained in the form of low-pressure steam or in the form of hot water. Obtained heat quality is dependent on two things, first, the type of fuel cell, and second its operating temperature. Hydrogen is used in the fuel cell as a fuel to achieve the best possible electrochemical reaction, and hydrogen is normally generated from coal, gas, methanol, natural gas, etc. (EPA 2017).

The biggest advantage of the fuel cell is that it does not release any toxic gases into the environment because the primary power conversion process of the fuel cell does not involve any combustion. The capital cost of the fuel cell is still high but it remains in demand for CHP applications due to low emission, low noise, good part load performance, and generous market subsidies (EPA 2017). Figure 6 shows diagram of a fuel cell-based micro-CHP system.

The main technologies of the fuel cells that are most widely used for domestic applications are PEMFC and SOFC.

2.4.1. SOFC (solid oxide fuel cell)

It works at high temperatures, the highest of all the types of fuel cells at around 800°C to 1,000°C. When converting fuel into only electricity, its efficiency is over 60%. If the

Table 5. Stirling engines commercially available and their characteristics.

Brand	Model	Electrical output (kW)	Thermal output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Noise (dB)	Dimensions (mm) (W × D × H)
Viessmann (2023)	Vitotwin 350F	1	3.6–26	15	96	-	-
Baxi (2023)	Baxi ECOGEN	1	7.7	-	90	-	450x426x950
Simons (Umayal and Kamaraj 2007)	QCHP-3500	3.5	14	20	103% LHV (Lower heating value); 91% HHV	50	-
Simons (Umayal and Kamaraj 2007)	QB-7500	7.5	30	20	103% LHV; 91% HHV	50	-
Inspirit (Furmanek and Kropiwnicki 2022)	Inspirit m-CHP	6.4	15	15	90	-	630x650x850
Okofen (Jenkins and Jackson 2010)	ÖkoFEN Smart_e	0.6	9	-	90	-	1,175x1,150x1,958

Table 6. Stirling engines advantages and disadvantages (EPA 2017).

Advantages	Disadvantages
Limiting wear on components and reducing vibration levels.	High economic cost of the engine
Few moving parts and good fuel versatility.	Reliability issue.
Constant burning of fuel as opposed to pulsed combustion reduces noise.	Low specific power and electrical efficiency.
Low emissions of NO_x and unburned fuels.	The heat transfer makes the engine far less responsive

produced heat is also harnessed, their overall efficiency can even reach over 90% when converting fuel to energy (Minh 2004). Figure 7 shows a micro-CHP system with a flame-assisted SOFC fuel cell. The advantages and disadvantages of Stirling engines are presented in Table 6.

2.4.2. PEMFC (proton exchange membrane fuel cell)

PEMFC uses a water-based system, an acidic polymer membrane as its electrolyte, with platinum-based electrodes. Normally PEMFC cells operate at relatively low temperatures (below 100°C) and can tailor the electrical output to meet dynamic power requirements (Powering the future of fuel cells fuel cells for decarbonising transportation and energy Lixin 2021). Figure 8 shows a schematic illustration of a house powered by PEMFC.

Table 7 shows a list of commercially available fuel cells with their characteristics.

Table 8 shows the comparison of fuel cell applications, advantages, and disadvantages.

The advantages and disadvantages of fuel cells are presented in Table 9.

3. Methodology

3.1. PESTLE analysis

The PESTLE analysis aims to give a concise overview of the external environment of an industry and the factors of deploying a technology (Political, Economic, Sociological, Technological,

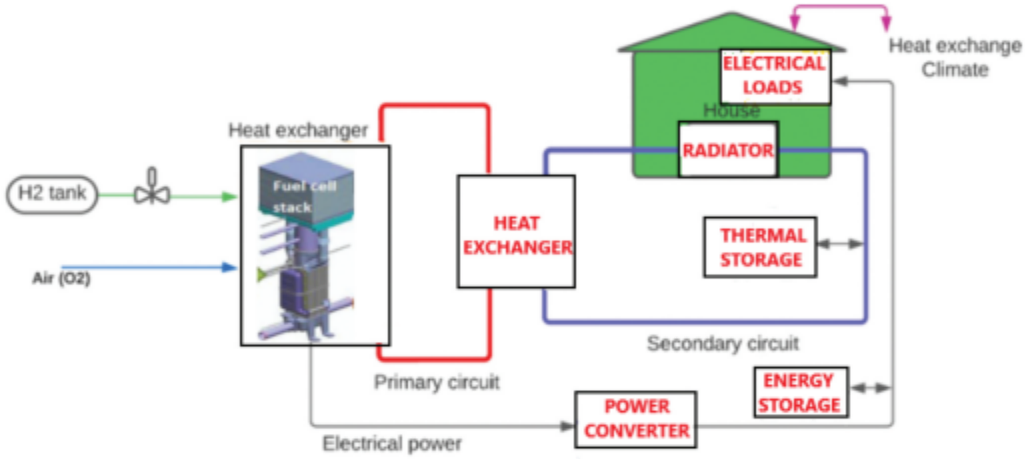

Figure 6. Fuel-cell-based micro-CHP system diagram, adopted from (Sanz i López, Costa-Castelló, and Batlle 2022).

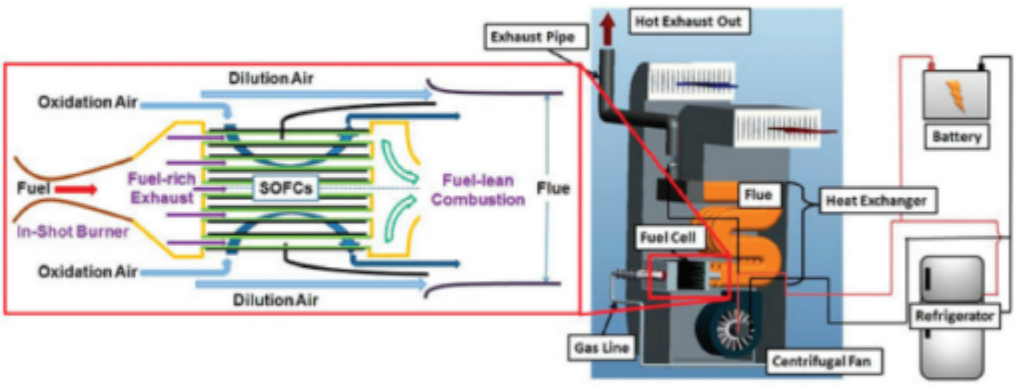

Figure 7. Micro-CHP system with a flame-assisted SOFC fuel cell (Wołowicz, Kolasiński, and Badyda 2021).

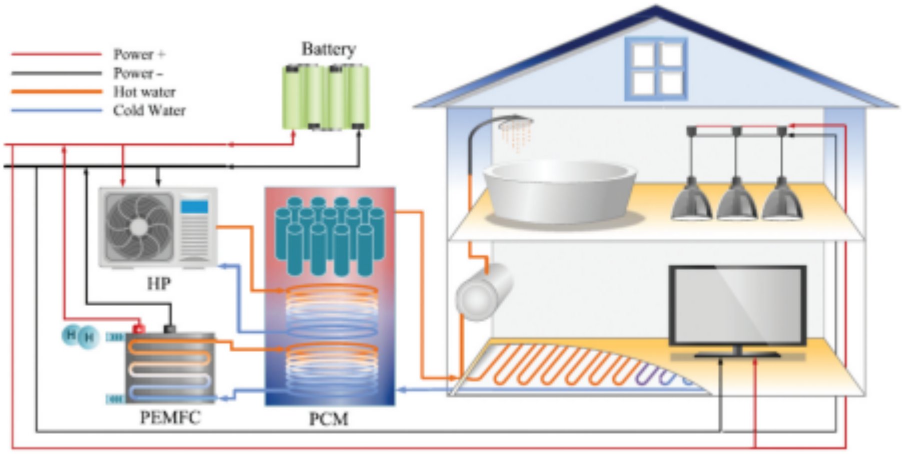

Figure 8. Schematic illustration of a house powered by PEMFC (Sun et al. 2021).

Table 7. Commercially available micro-CHP systems with fuel cell core engine and their characteristics.

Brand	Model	Types	Electrical output (kW)	Electrical efficiency (%)	Overall efficiency (%)	Dimensions (mm) (WxDxH)
Bluegen (Dukes 2001)	BG-15	SOFC	1.5	55	88	550x800x1200
Elcore (2020)	Elcore 2400	HTPEM technology	0.3	32	-	600x550x1050
Elcore (Industriesysteme H. VITOVALOR 300-P n.d 2023)	Vitovalor 300-P from Viessmann	Low temperature PEM	0.75	37	>90	600x595x1932
Hexis (2023)	Galileo 1000 N	SOFC	1	35	95	620x580x1640
KD Fuel Cell (2013)	IRD Fuel Cell	PEM	1.5	-	94	-
Baxi Innotech Gamma 1 (2011)	Gamma 1.0	PEM	1	32	>95	600x600x1600
VIESSMANN (2019)	Vitovalor PT2	PEM	0.75	37	92	1200x595x1800

Table 8. Comparison of fuel cell applications, advantages, and disadvantages (EPA 2017).

Fuel Cell Types	Applications	Advantages	Disadvantages
Alkaline (AFC)	• Military • Space	• Cathode reaction faster in alkaline electrolyte leads to high performance • Low-cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Direct Methanol (DMFC)	• Backup power • Portable power • Military	• No need for reformer (catalyst separates H2 from liquid methanol) • Low temperature	• Expensive catalysts • Low-temperature waste heat
Phosphoric Acid (PAFC)	• Auxiliary power • Electric utility • Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Platinum catalyst • Startup time • Low current and power
Proton Exchange Membrane (PEMFC)	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick startup	• Expensive catalysts • Sensitive to fuel impurities • Low-temperature waste heat
Molten Carbonate (MCFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High-temperature corrosion and breakdown • Long startup time • Low power density
Solid Oxide (SOFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & Combined heat, hydrogen, and power Hybrid/GT cycle	• High-temperature corrosion and breakdown of cell components • High-temperature operation requires a long startup time and limits

Table 9. Fuel cells advantages and disadvantages (EPA 2017).

Advantages	Disadvantages
Low emissions.	High costs.
High-efficiency overload range.	Fuels require processing unless pure hydrogen is used.
Modular design.	Sensitive to fuel impurities.
Low noise.	Low power density.

Legal and Environmental). Table 10 summarizes the critical data used in this PESTLE analysis.

The elements found in the **political** aspect refer to the incentives relative to enshrining in law a commitment to reach net-zero emissions. These incentives vary widely by country. The UK government has committed to reaching net zero carbon emissions by 2050 and even pushed the target date in most of the sectors to 2030. Germany and France have also agreed and want the EU to agree on a net zero carbon emission target by 2050. Also, Denmark, Belgium, Portugal, Spain, the Netherlands, Sweden, and several other European countries are supporting the net zero carbon emission goal by 2050. But there are also some eastern and central European countries that are opposed to that (Skeete 2019).

The **economic** aspect is looking at the cost per kilowatt of the unit. However, to evaluate the economic profitability of a unit other technical parameters and incentives have also to be taken into account. The prices of kilowatt units vary from £720 to 5217/kWe, depending on the different techniques of prime movers (EPA 2017; Houssein, Fardoun, and Louahlia 2017; Laurence, Greening, and Azapagic 2017).

The **social** aspect has been estimated based on the willingness to pay citizens in different countries. However, it appears that, currently, there are more than 50 products identified worldwide as micro-scale of cogeneration appliances from more than 30 manufacturers (generally <50 kWe). Integration of these types of devices into residential and household applications worldwide has not been completely developed and successful because of several reasons including slow implementation, immature technology, and less awareness. It is believed that it will become a part of the energy market soon after the integration of small-scale CHP systems with renewable energy systems in residential buildings (Murugan and Horák 2016).

The **technical** part of the PESTLE is the most important aspect because it is the one that displays the largest differences between the technologies. The technical parameters selected for this part were start-up time, overall efficiency, size, range of power, power-to-heat ratio, part-load performance, and availability. These data are summarized in Table 10.

The **legal** aspect is under the responsibility of the micro-generation certification scheme. It specifies that the size of a micro-CHP unit must be below 50 kWe or 45 kWth. It needs also comply with the following assumptions: the micro-CHP unit is the main heating system; it acts as a boiler substitute and must display better environmental benefits and efficiency; it provides heating service throughout the year; it is controlled by heat demand; heat is never wasted; and the electricity, if produced in excess, can be exported to the grid. It also has to respect the electrical safety council requirements: "Connecting a micro-generation system to a domestic or similar electrical installation" (Microgenerationcertificationscheme WG 8. 2012).

The **environmental** aspect has been restricted to emissions and noise levels. The noise level is linked to the comfort of the resident of the household and the particulate emissions are linked to existing standards. Table 10 shows the critical data used in the analysis of PESTLE.

3.2. MCDA analysis

A Multi-Criteria Decision Analysis (MCDA) is a mathematical tool that takes into account technical and non-technical information to select the best option among several alternatives. Due to the high number of parameters that characterize the micro-CHP technology, an MCDA was therefore completed. This MCDA allowed finding out the most suitable option for a domestic application. The first step of the analysis was to define the criteria used to assess the suitability of the four systems. To take into account all the important factors, the PESTLE risk analysis performed for each technology has been followed. The criteria chosen are given in Table 11.

Once all the criteria were defined, they were ranked in terms of importance. All the criteria related to the prices or that influence the economic benefits were considered the most important (the price of the unit and installation, overall efficiency, and power-to-heat ratio). They were followed by the criteria related to the environment (emissions but also noise and size of the appliance) and finally the operational issues (power range, part-load performance, start-up time, and availability). The software Decerns MCDA was used to calculate the weight for each criterion. After that, using the results of the PESTLE risk analysis, each technology received a mark between 1 and 8 for each criterion. The scores obtained were multiplied by the weight of each criterion and summed to get the final results for each technology.

4. Results and discussions

The MCDA results allowed finding the most suitable option for a single home application. The scores obtained by the different technologies are shown in Figure 9.

Taking into account all these criteria, Fuel cells seem to be one of the best options for domestic applications. The technology leads in terms of environmental impacts (noise and emissions), has very good technical aspects (high efficiency, good availability, and part-load performance), and is the most accepted by consumers. Its high price is compensated by the incentives received for the electricity produced. However, incentives are high in Germany and the UK and are reasonable in France and Belgium, but in the other European countries,

Table 10. Prime movers' main characteristics summary.

	Prime movers	Reciprocating engines	Stirling engine	Fuel cell	Micro-gas turbine
	Type of Application	Heating and sanitary water; Future development in trigeneration; Emergency generator	Space heating and sanitary water; Heat storage for longer electrical production	Space heating and sanitary water; High power-to-heat ratio so very valuable for electricity generation	CHP and trigeneration; Widespread monitoring availability, smart-grid frameworks
P	It depends widely on the country. The best is Germany, France, and the United Kingdom				
E	Cost ($/kW)	900–1500 (Houssein, Fardoun, and Louahlia 2017)	3700 (£2937) (Laurence, Greening, and Azapagic 2017)	5000–6500 (EPA 2017)	1300–2500 (Houssein, Fardoun, and Louahlia 2017)
S	The willingness to pay for fuel cells is higher than for the other technologies				
T	Fuel	natural gas, biogas, LPG, sour gas, industrial waste gas, manufactured gas (EPA 2017)	Any fuel (SGC 2004)	hydrogen, natural gas, propane, methanol (EPA 2017)	Natural gas, waste and sour gases, gasoline, kerosene, diesel, distillate fuel oil (Houssein, Fardoun, and Louahlia 2017)
	Size (m^3)	0.77	0.19	1.26	0.63
	Overall CHP Efficiency	86.7–94.9 (Breeze 2018; Freng, Turan, and Ther- 2019)	90–96 (EAW 2014; Udeh et al. 2021)	88 - >95 (Jenkins and Jackson 2010; Wołowicz, Kolasiński, and Badyda 2021)	80 - >94 (EPA 2017; Samad 2019)
	Power-to-heat ratio	0.5–1.2 (EPA 2017)	0.1–0.4 (VGB 2016)	1–2 (EPA 2017)	0.5–0.7 (EPA 2017)
	Part Load	Good (Houssein, Fardoun, and Louahlia 2017)	Good (SGC 2004)	Good (EPA 2017)	Satisfied (Houssein, Fardoun, and Louahlia 2017)
	Availability	96–98 (EPA 2017)	99% (EPA 2017)	99% (EPA 2017)	98–99% (EPA 2017)
	Start-up Time	10 s (EPA 2017)	20 min–1 hr (VGB 2016)	3 h–2 days (EPA 2017)	60 s (EPA 2017)
L	micro-CHP unit must be: below 50 kWe or 45 kWth; the main heating system; act as a boiler substitute; must display better environmental benefits and efficiency; provide heating service throughout the year; be controlled by heat demand; never waste heat and electricity – if produced in excess, can be exported to the grid.				
E	Noise	High (Houssein, Fardoun, and Louahlia 2017)	Low (SGC 2004)	Low (VGB 2016)	Moderate (Houssein, Fardoun, and Louahlia 2017)
	NO_x (kg/MWhe)	0.99 (kD Fuel Cell 2013)	0.63 (kD Fuel Cell 2013)	0.011–0.016 (EPA 2017)	0.14–0.49 (EPA 2017)
	CO_2 (lb/MWhe)	650 (Houssein, Fardoun, and Louahlia 2017)	999.72 (EPA 2017)	980–998 (Laurence, Greening, and Azapagic 2017)	720 (Houssein, Fardoun, and Louahlia 2017)
	Comments	Significant heat recovery potential (around 60%); low output temperatures	Easy installation; Thermal storage could significantly enhance its electric energy delivery	Good power quality, catalyst could be expensive and highly sensitive to impurities	Compressor is required. This appliance could vary its yield depending on ambient conditions

Table 11. Criteria used to perform MCDA.

Ranking (importance)	Criteria	Definition
1	Price (£/kW)	Price of the unit and installation
2	Overall efficiency (%)	The higher the efficiency, the higher energy amount is produced with the same quantity of fuel.
3	Power-to-heat ratio	A high P/heat infers that more electricity is sent to the grid (or less is imported) so it is economically attractive (if incentives are available).
4	Noise	Low noise is required for the comfort of the residents.
4	Size of the unit (m^3)	The unit has to be not too cumbersome to fit in the house.
5	Willingness to pay (WTP)	The higher the WTP, the more willingly people accept the technology.
5	NO_x (kg/MWh)	The emissions must be below to not impact on residents' health and the environment.
5	VOC (kg/MWh)	
5	CO (kg/MWh)	
5	CO_2 (kg/MWh)	
6	Power range (kW)	The technology has to be able to meet the low domestic demand (about 1 kWe).
7	Part-load performance	Part-load performance is important to avoid losses of energy due to over-production
8	Start-up time	Domestic demand can vary quickly, the system has to respond rapidly
8	Availability	Availability characterizes the maintenance needed on the unit; if the availability is high the unit can work longer and the cost for maintenance would be lower.

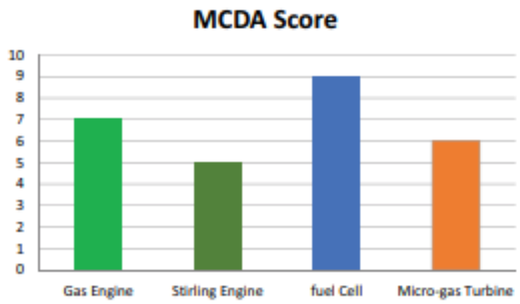

Figure 9. Results of the MCDA for different prime movers in micro-CHP systems.

incentives for electricity generation and sale are low. In these countries, the high power-to-heat ratio is not necessarily a valuable parameter. If the contribution of the power-to-heat ratio is deleted in the analysis, the Stirling engine score almost reaches that of the fuel cell. Improvements in the fuel cells have to be made to decrease the high price of this system because it is the main barrier to its market improvement.

The Stirling engine is a promising prime mover that recived the minimum MCDA score in this study. However, thanks to its high production of heat, low noise level, reasonable price, and good dimensions, it can easily fit in a house. The environmental aspects and flexibility of operation (start-up time and part-load performance) must be improved for this technology to be attractive. The MCDA results show that Gas engines are the second appropriate option for the domestic applications. Their high availability, short start-up time, and good part-load performance make them suitable for emergency use in hospitals or retirement residences and bigger residentials houses.The micro-gas turbine is, according to this study, the least explored and an emerging option for the households' applications. The power output of this technology has to fit with the requirements of the residential market to make this system probably the most cost-effective option with a good overall efficiency in the market. Research isto be carried out into adjusting micro-gas turbines' power capacity, increasing the electrical efficiency and operational flexibilities, and controlling emissions (noise and gases) it could become a very interesting option. Figure 10 summarizes the strengths and drawbacks of each technology using MCDA. As the values of the data varied widely, the feature scaling method was used to normalize the data. Values between 0 and 1 were obtained and were used to build the radial graphs in Figure 10. It is important to specify that the charts present relative values and not the absolute ones. Figure 10, the closer the value is to 1, the more the technology has good performance for the criterion. For example, the overall efficiency of the gas engine is suitable for household applications, whereas the price of the fuel cell is not well adapted. The MCDA analysis shows that fuel cell technology receives the highest overall mark for domestic applications due to the environmental benefits, lower noise level, good part load performance, and heat-to -power ratio. Gas engine technology, however, is the most developed technology with the highest electrical efficiency around 40% but having noise and vibration challenges. Stirling engine technology is a well established and fuel flexible technology, but it lacks the electrical efficiency and the heat recovery rate. Microturbine technology as an emerging technology to the micro-CHP market receives a moderate range of scores on all defined criteria in the web graph and it receives a better overall score as compared to the Stirling engine micro-CHP systems. The MGT Micro-CHP systems are highly reliable, cost-effective, and fuel-flexibleable to operate continuously for long periods with minimal maintenance.

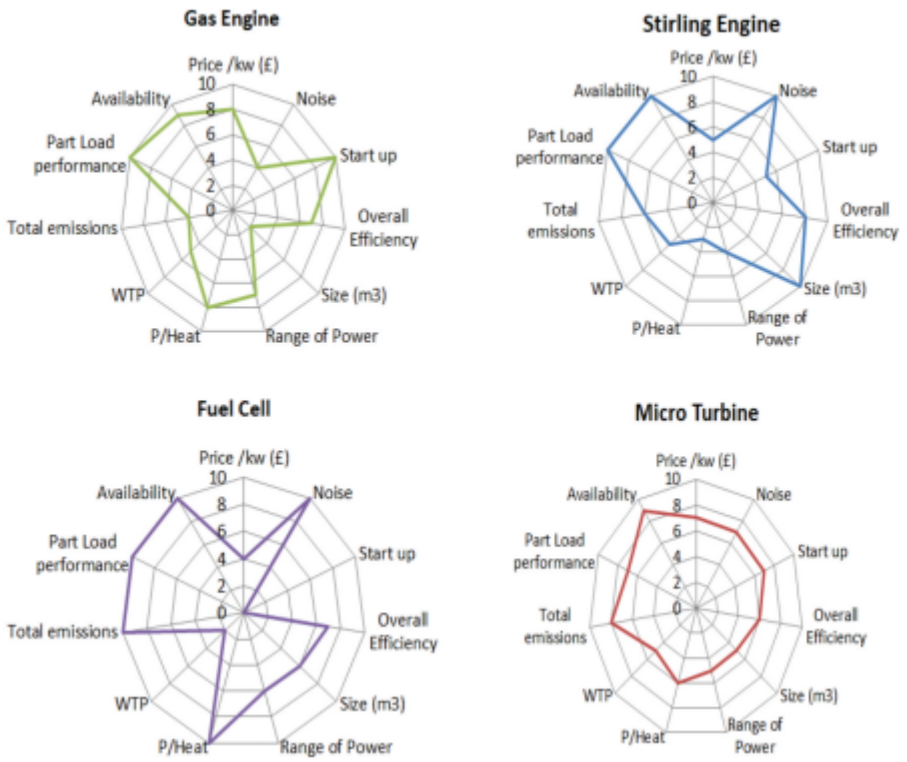

Figure 10. Characteristics of each prime mover according to the MCDA (Baxi Innotech Gamma 1 2011; Hexis 2023; Industriesysteme H. VITOVALOR 300-P n.d 2023; KD Fuel Cell 2013; Samad 2019; VIESSMANN 2019).

5. Conclusion

This paper has independently assessed different technologies available for micro-CHP systems, gas engines, Stirling engines, fuel cells, and micro-gas turbines. The advantages and disadvantages of different solutions are evaluated to present a clear overview of the state of the art in micro-CHP systems and the available products in the market for domestic applications. Risk analysis of the deployment of all these technologies has been evaluated using PESTLE risk analysis. Furthermore, using MCDA software, the technologies are evaluated to present the best products for the household domestic application.

Gas engines have particularly good start-up time, the best technology maturity, and high electrical efficiencies. Stirling engines are already commercially available, with a good range of products, a low level of noise, and the size of the units are appropriate for most types of dwellings; however, considerations for more improvements in electrical efficiency are required. Micro-gas turbines have been attracting more attention recently due to their lower price, compact design, low maintenance cost, and the possibility of accommodating CCS techniques and burning carbon-neutral fuels (i.e., biogas, H_2). The fuel cell is a technology that is emphasized for its very low emission and noise level. The higher price of the system might be compensated by the high power-to-heat ratio and the high availability which allow selling electricity to the grid in countries where incentives are available, such as the United Kingdom and Germany. The startup time for the fuel cell systems is much higher as compared to the other technologies and needs a continuous operation.

Micro-gas turbines have a low price per kilowatt, much lower start-up time compared to fuel cell systems, and lower emissions compared to gas engines. They also have acceptable noise levels, fuel flexibility, and maintainability. The inadequate range of power for domestic applications should be addressed by companies currently working on the development of these systems for the household market. In terms of fuel flexibility and emission control, it appeared that some units, such as Stirling engines and micro-gas turbines, are more prone to tolerate unconventional fuel, whereas fuel cells and reciprocating engines are more sensitive to impurities. In addition, the integration into the grid or the creation of a micro-grid is a promising field where many improvements related to congestion or security of supply in isolated areas can be realized.

The MCDA analysis shows that fuel cell technology receives the highest mark for domestic applications due to the environmental benefits of the technology; however, the price range should be moderated by technology improvements. Gas engines receive the second score due to technical reliability and maturity, but the noise level and product availability in lower ranges (1–5 kWe) should be addressed by boiler companies. Microturbine technology as an emerging technology in micro-CHP systems receives the third rank with a moderate range of scores in all the defined criteria. Stirling engine technology has the benefits of low cost, good availability of products, and fuel flexibility, but electrical efficiencies should improve. Electrical production of micro-CHP systems can have efficiencies of up to 40% and overall combined heat and power efficiencies of over 90%. Micro-CHP systems coupled with renewable energy technologies and biofuel and H_2 are one of the best solutions providing on-demand clean, flexible, and predictable decentralized energy for households and domestic applications for the transition to net-zero buildings.

Highlights

- Technoeconomic analysis of four major m-CHP prime movers (i.e., micro-gas turbine, gas engine, Stirling engine, and fuel cell) is performed.
- Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) risk analysis shows pros and cons of deploying mCHP systems for domestic application.
- The most suitable options for household applications were identified by means of Multi-Criteria Decision Analysis (MCDA).
- Micro-gas turbine and Stirling engines are fuel flexible and cost competitive. Fuel cells are the most environment-friendly option, and gas engines are the most developed technology.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Credit author statement

Prof Hamidreza Gohari Darabkhani performed conceptualization, supervision, reviewing, and editing work.

Muhammad Asim Khan performed writing original draft preparation, software work, and methodology.

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Low-carbon fuelled MGT-CHP system coupled with PEM electrolyser and fuel cell units: A fuel flexibility and performance study

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Low carbon fuel

A B S T R A C T

Recently, micro gas turbine (MGT) systems for combined heat and power (CHP) plants have attracted much attention due to their high combined energy efficiencies and low carbon emissions. Therefore, this study has focused on the performance and fuel flexibility analysis of a 5.5 kW MGT-CHP system coupled with a proton exchange membrane (PEM) electrolysis cell and a fuel cell unit for domestic applications. The simulation study includes an MGT unit that produces both heat and electricity, a low-temperature PEM electrolysis of H_2O to produce H_2 fuel for the combustor, and a PEM fuel cell to generate electricity during system initialisation. The MGT unit in this study uses H_2, hythane (20% H_2 + 80% CH_4), natural gas (NG) and methane (CH_4) fuels to investigate the thermal and electrical efficiency and CO_2 emission avoidance for each fuel utilisation. The result shows that the combustion of H_2 and hythane in the MGT combustor produces almost the same amount of nitrogen oxides (NOx) due to the lower reaction temperature of the combustor. Nearly 7% of CO_2 and CO emissions were avoided by replacing NG with hythane. CO_2 and CO emissions were avoided by burning H_2 instead of other fuels. Higher thermal efficiency was seen on the H_2-fuelled MGT system. However, higher end-use costs were observed for the MGT system running on both H_2 and hythane fuels due to the higher purchase price of both fuels. The addition of a recuperator promoted lean combustion, which improved the overall efficiency of the proposed system. The outcome of the studied work achieved an efficiency of 82% for PEM electrolysis of H_2O and an MGT-CHP combined efficiency of 96%.

1. Introduction

The global average temperature of the earth is constantly rising and the actual warming over the 20th century reached about 0.6 °C. Today, the surface temperature is around 1.2 °C above the avarage pre-industrial levels (13.68 °C). Due to increasing level of greenhouse gas (GHG) emissions, the temperature is projected to increase by up to 2.4 °C by the end of the 21st century based on the Stated Policies Scenario (STEPS) [1]. In the Net Zero Emissions by 2050 (NZE) Scenario, the temperature falls to around 1.4 °C in 2100 [1]. Climate change effects such as sea flooding due to rising sea levels, acid rain, severe cold winters, and heat wave summers are effects of continuous GHG emissions [2]. In 2015, 196 Parties at the UN Climate Change Conference (COP21) in Paris reached an agreement to reduce greenhouse gas emissions to avoid impossible reversals of climate change. Such an agreement also includes keeping the temperature rise well below 2 °C by the mid-century. To prevent such irreversible climate change, transition to low-carbon fuel, and renewable energy systems, improve in end-use efficiency, and carbon capture and storage were proposed to keep the temperature increase below 2 °C by 2030 [3]. Although net targets for carbon dioxide (CO_2) emissions by 2050 are necessary to reduce global warming. Achieving this goal requires a significant reduction in CO_2 emissions as it is the highest among other GHG emissions in all economic sectors [4,5]. The increase in CO_2 emissions is due to the burning of hydrocarbons and solid fuels to generate heat and electricity in many sectors such as agriculture, utilities, transportation, etc [6].

The CO_2 emission from the utility has increased because of fossil fuels' combustion in an internal combustion engine (ICE) to produce electricity in higher demand. For example, it is predicted that by 2040, the demand for energy will increase by 56%, and approximately 66% of the thermal energy from ICE is unused during combustion. Utility energy usage can be classified to residential, commercial, and industrial sectors and accounts for 74% of the total energy demand. For example, the share of the residential sector is 21%, the commercial sector is 22% and 31% for the industrial sector. The remaining 26% of the total energy demand goes to the transport sector [7,8]. The building sector is one of the most important energy-consuming factors [9]. According to the

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Nomenclature

Abbreviations and Symbols

micro-CHP	Micro-Combined Heat and Power system
FC	Fuel Cell
NG	Natural Gas
IEA	International Energy Agency
ICE	Internal combustion engine
NOx	Nitrogen Oxides
MTT	Micro turbine technology
PEME	Proton-exchange membrane electrolysers
SOSE	Solid oxide steam electrolysers
STEPS	Stated Policies Scenario
NZE	Net Zero Emissions by 2050
PEMFC	Proton exchange membrane fuel cell
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Isobutane
C_4H_{10}	n-butane
C_5H_{12}	Isopentane
C_6H_{14}	Hexanes
O_2	Oxygen
MGT	Micro Gas Turbine
GHG	Greenhouse Gas
CO_2	Carbon Dioxide
CO	Carbon monoxide
kW	Kilowatt
AWE	Alkaline water electrolyser
NRTL	Non-Random Two-Liquid
CH_4	Methane
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
N_2O	Nitrous oxide/Oxide of nitrogen
N_2O_5	Dinitrogen pentoxide/Nitrogen Pentoxide
CC	Combustion Chamber
C_5H_{12}	n-pentane
C_7H_{16}	Heptanes

International Energy Agency's 2022 report, buildings used about 34% of the world's total energy and generated about 37% of CO_2 in 2021. Due to population growth, electricity transmission losses and inefficient domestic gas boilers, the demand for energy in buildings is projected to grow to become the largest energy-consuming sector by 2040 [9,10]. For these reasons, the use of low-carbon fuels in efficient small-scale heat engines and adaptation of renewable energy sources are required to reduce CO_2 and other GHG emissions. Micro gas turbines (MGT), which have gained a lot of attention in recent years, can play an important role in improving efficiency and reducing GHG emissions in the building energy sector [6,11]. Fig. 1 shows comparisons of building energy consumption and GHG emissions in the USA, Europe, and the UK [12]-.

MGT systems are small types of gas turbines that can generate both heat and electricity. Some of the advantages include, small-scale units, low maintenance costs, low weight and emissions, ease of use, decentralised energy, and fuel flexibility [6,11]. The first gas turbine technology with an output of 370 kW was developed by Holz in the 1920s. Although the micro-scale gas turbine system was launched in the 1950s. This system uses a high-speed generator connected to the turbine, a recuperator to recover waste heat, and other components to improve compactness and maximise the overall efficiency by 10%. In addition, the use of high-temperature materials to increase the turbine inlet temperature (TIT) to 900–1200 K, further increased the thermal efficiency to about 35% [11]. Initially, gas turbine systems were designed

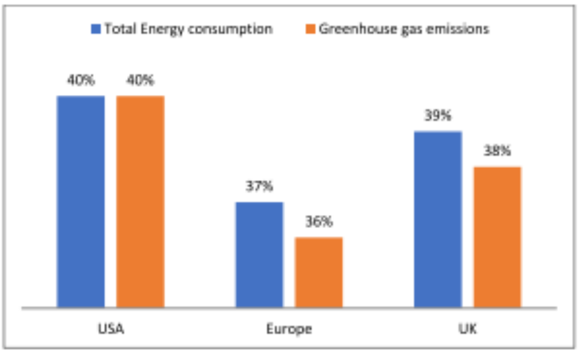

Fig. 1. Comparisons of the building energy consumption and GHG emissions in the USA, Europe, and UK.

for powertrains and large-scale power distribution sectors. A combined heat and power (CHP) system based on MGT was introduced for a proper distribution of power in microgrid systems [11]. Nowadays, European countries have increased research on the integration of MGT systems into other units to reduce the operational cost of standalone MGT units. For instance, the techno-economic analysis result of hybrid MGT and other renewable energy units such as solar cells, a wind turbine system and a battery revealed that lower operational costs are feasible compared to a hybrid diesel generator or fuel cell coupled with any of these units (solar cells, wind turbine system and battery) [13]. The lower operation cost of MGT-CHP systems is partly related to a feed-in tariff to offset investment costs. Apart from the lower operation cost of integrated MGT systems, the use of low-carbon fuels such as mixtures of natural gas (NG) with biogas, syngas or hydrogen in MGT-CHP systems can significantly reduce CO_2 emission up to 40% [14,15]. Despite carbon reduction by transitioning to the NG-MGT system, 56.4 Mt of CO_2 came from UK residential and public sectors that use NG-fuelled gas boilers [16]. Unlike the NG-MGT system for small-scale utility systems, the H_2-fuelled MGT-CHP system has been suggested to help achieving net-zero targets in residential and domestic energy market by 2050. For instance, replacing NG with grey H_2, 220g $CO_2eq./kWh$ of heat associated with NG based gas boiler could fall to 64g CO_2 $eq./kWh$. This CO_2/kWh value of grey H_2-fuelled gas boiler could be avoided by using biohydrogen or green H_2 fuel from the electrolysis of H_2O [17]. Nonetheless, the thermal stress of combustor or cylinder walls, flame instability and the short reactant residence time which increases NOx formation are drawbacks of H_2-based heat engines [18–20]. A micro-CHP energy flow diagram for residential applications is displayed in Fig. 2. Table 1 shows

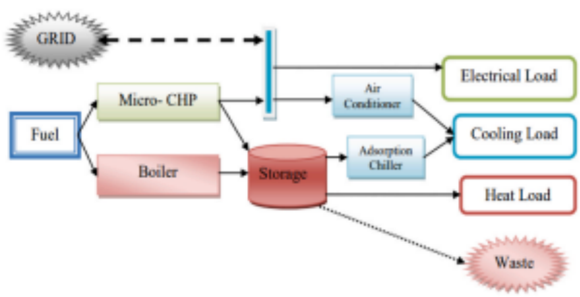

Fig. 2. Micro-CHP energy flow diagram for residential applications [21].

Table 1
The properties of the four types of MGT fuel [22–24].

Properties	Fuel type				Unit
	Hydrogen (H_2)	Hythane (20% H_2 + 80% CH_4)	Natural gas (NG)	Methane (CH_4)	
Lower heating value	120	70–75	42–55	50–55	MJ/kg
Density	0.09	0.4	0.72	0.657	kg/m^3
Boiling point	−253	−198	−161.5	−162	°C
Stoichiometric AFR	34.3	22.58	17.12	17.19	kg(a)/kg(f)
Stoichiometric CO_2 emissions	0	38.2	54.9	55	mass%
Flame speed	1.85	0.68	0.38	0.39	m/s
Minimum ignition energy	0.02	0.19	0.31	0.28	MJ
Latent heat of vaporization	–	–	509	510	kJ/kg

the properties of the four types of MGT fuel (i.e., Hydrogen, Hythane, Natural gas and Methane).

The electrolysis of H_2O is a process where H_2O is split into H_2 and oxygen (O_2) using electricity. There are three main technologies of H_2O electrolysis such as proton exchange membrane electrolyser (PEM), alkaline water electrolyser (AWE) and solid oxide steam electrolyser (SOSE). The first two techniques (AWE and PEME) work at low temperatures, but the third (SOSE) works at high temperatures [25]. The production of H_2 using electrolysis methods is one of the most important advances in reducing carbon emissions [26]. Among the three main types of H_2O electrolysis, some of the advantages of PEMWE are high current density, fast response time, purity, and operating pressure. Integrating PEMWE into a micro-CHP system to produce heat, electricity and H_2 fuel offers more environmental benefits compared to a single NG-based micro-CHP system. In such a hybrid system, the electricity generated by the prime mover of the micro-CHP system which is sold to the grid at a cheaper rate can replace the grid electricity in the electrochemical splitting of H_2O process to produce H_2 [27]. For example, *Nami* et al. [28] reported 56.2 kg/h and 49.2% exergy and energy efficiencies of combined PEMWE and organic Rankine cycle system for H_2 production. Additionally, *Ferrero and Santarelli* investigated an integrated PEMWE and high-pressure, low-temperature multi-junction solar system and reported improved performance of the system [29]. Similar to the integrated PEMWE-CHP, the hybrid micro-CHP and proton exchange membrane fuel cell (PEMFC) system is one of the viable options for low-carbon emission and noise reduction [28,30]. A hybrid PEMFC-based micro-cogeneration system can reduce CO_2 emission and total energy consumption and co-produce heat and electricity using H_2 as fuel [31]. For example, Lümmen et al. [27] reported 76.94% and 53.86% energy and exergy efficiencies during a study of micro-combined cooling, heating, and power systems (MCCHPs). The researched work also reported CO_2 emission of 2.8 k/h. While an integrated micro-CHP plant, PEM electrolysis and fuel cells, and solar or wind renewable energy systems can simultaneously generate electricity at a cheaper rate compared to a single H_2-fuelled MGT system [27].

To promote low-carbon buildings and improve the efficiency of the current micro-CHP system, this study aimed to simulate an integrated MGT-CHP system, coupled with PEM electrolyser and fuel cells units for the first time. The purpose of this work is to investigate the effect of H_2, natural gas (NG), CH_4 and hythane (mixture of H_2 and CH_4) combustion and analyses of CO_2 and thermal nitrogen oxide (NOx) emissions. Instead of selling the generated electricity to the grid at a lower price and buying it at a higher price, the generated electricity will be used to operate the downstream units such as PEMWE. Produced H_2 from the combined system will also be utilised to generate electricity via FC during system initialisation and as combustion fuel. Unlike the current micro-CHP unit, this simulated system intends to increase the electrical power output by reducing the heat output for applications that require more electricity.

2. Methodology

To achieve the target power of 5.5 kW, Aspen Plus process simulation software was used with H_2, CH_4, NG and hythane as combustion fuel. A rigorous reactor (RGibbs) was considered to simulate the fuel combustion and electrolysis of H_2O using proper electrochemical reactions in the chemistry ID. Other Aspen Plus core components included in this simulation are pumps, compressor, turbine, recuperator (heat exchanger), switch, mixer, splitter, and calculator block. The upstream intake parameters of the proposed system are shown in Table 2. The simulation method of this proposed system is categorised in the below scenarios:

Table 2
MGT combustor inlet and outlet parameters.

Property/Parameter	Value	Unit
MGT combustor intake fuel pressure	2.09	bar
MGT combustor intake fuel temperature	970	K
Air mass flow rate	0.053	kg/s
MGT burner exit temperature	1323.4	K

- Aspen Plus process simulation of an existing MGT-based micro-CHP system to improve knowledge of the proposed model.
- Aspen Plus process simulation for the proposed model which includes a micro-CHP system running on hydrogen (H_2), hythane, NG and CH_4.

2.1. Process simulation of existing micro-CHP system and proposed innovative system in Aspen Plus

The process simulation of the existing micro-CHP system and the proposed model were carried out in Aspen Plus and both the Peng-Robinson and Non-Random Two-Liquid (NRTL) equations of states were employed with mixed as the only substream. The assumptions considered in both process simulations are described below:

- All processes are in steady state condition.
- Intake feed temperature and pressure is ambient and atmospheric conditions.
- The pressure drop at each stage is minimal.
- 78% nitrogen, 21% oxygen, and 1% argon mole flow are the compositions of air fed to the system.
- Dry NG is composed of 96% CH_4 (methane), 2% C_2H_6 (ethane), 0.60% C_3H_8 (propane), 0.18 C_4H_{10} (isobutane), 0.12% C_4H_{10} (n-butane), 0.14% C_5H_{12} (isopentane), 0.06% C_5H_{12} (n-pentane), 0.10% C_6H_{14} (hexanes) and 0.80% C_7H_{16} (heptanes) [32].
- Oxides of nitrogen (NOx) include nitric oxide (NO), nitrogen dioxide (NO_2), nitrous dioxide (N_2O) and nitrogen pentoxide (N_2O_5).
- 80% of CH_4 and 20% of H_2 are composition of hythane.
- Electrolysis of H_2O to generate H_2 for hythane using the electricity generated from the proposed system.
- H_2 fuel cell to generate electricity for the motor during the start-up of the proposed system.

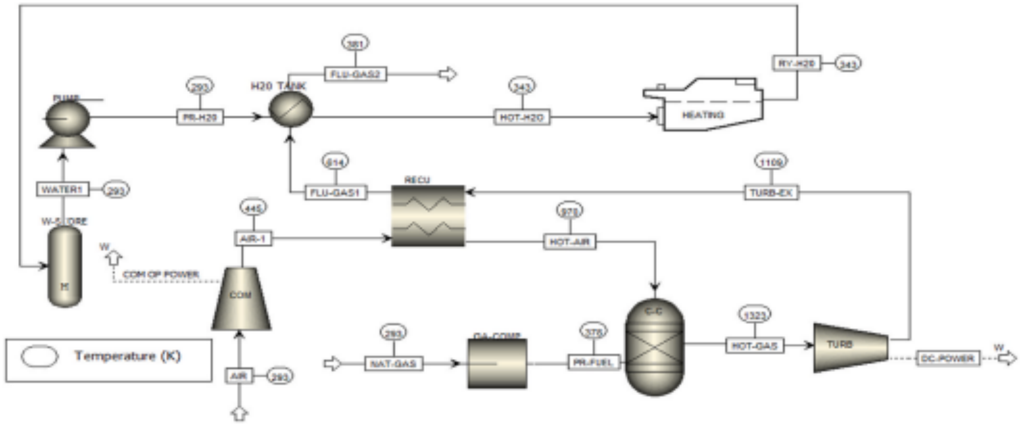

Fig. 3. Aspen Plus process diagram of MGT-CHP system operating with NG.

- Air fed to the combustor is preheated by a recuperator (heat exchanger) unit to maximise the overall efficiency.

Fig. 3 shows an NG-operated micro-CHP system for heat and power production. In the process flow diagram, air at 0.053 kg/s is compressed to a pressure of 2.9 bar in the compressor and sent to the recuperator system to increase the temperature to 970 K. Pressurised hot air from the recuperator is combusted with pressurised NG at a ratio of 106:1 in the combustion chamber (CC). The hot gas leaves the CC at a temperature of 1323.4 K to a turbine where electricity is generated. The hot gas in the turbine creates a rotatory motion that turns an electricity generator for the conversion of mechanical energy to electrical energy with 5.5 kW power output. The low-pressure hot flue gases exiting the recuperator preheat the combustor air intake before heating the water (H_2O) molecule in another heat exchanger. In a hot H_2O heating system, the cold H_2O from the storage tank is pressurised by a pump before absorbing heat from the flue gases. This is a continuous cycle to provide hot water and heat the environment while the micro-CHP system is in operation. During the system start-up time, electrical energy from the grid is needed to ramp up the compressor for air intake with the use of an electric generator which in turn, works as a motor. In the final stage, the exhaust gas which is a mixture of carbon dioxide (CO_2), nitrogen gas, oxides of nitrogen (NOx) and others from the H_2O heater is discharged into the environment.

Similar to a conventional micro-CHP system, the proposed model shown in Fig. 4 uses H_2 gas, hythane, NG and CH_4 gas as fuel. Proton exchange membrane (PEM) electrolysis of H_2O and H_2 fuel cells were introduced to generate H_2 feedstock and electricity for the motor during start-up time. The motor which is also an electric generator spins the compressor during the initiation period to suck air in and increases the pressure. Unlike a conventional micro-CHP system, the proposed model has a fuel-switching unit, mixer, splitters and motor-electricity generator. The fuel-switching unit allows one fuel to be used at a time to monitor the heat output of the combustion chamber (CC). The mixer (mix) mixes both the H_2 feed and the H_2 by-product of the PEM electrolyser unit to feed CC. The motor rotates the compressor at a speed of 240,000 rpm during the kick-off time. While a controlled amount of O_2 gas into the PEM fuel cell (PEMFC) was possible by using an oxygen (O_2) splitter. Similarly, the H_2 gas splitter controls the flow rate of H_2 gas to the combustor and PEMFC to generate electricity for the motor. The calculator block estimates the power output of the proposed system by subtracting the input powers of the air and gas compressors and a pump from the output power of the turbine. The rest of the unit has the same working principle as the conventional micro-CHP system. This developed system also has the potential to increase the output power by reducing heat production in applications where less thermal energy is needed.

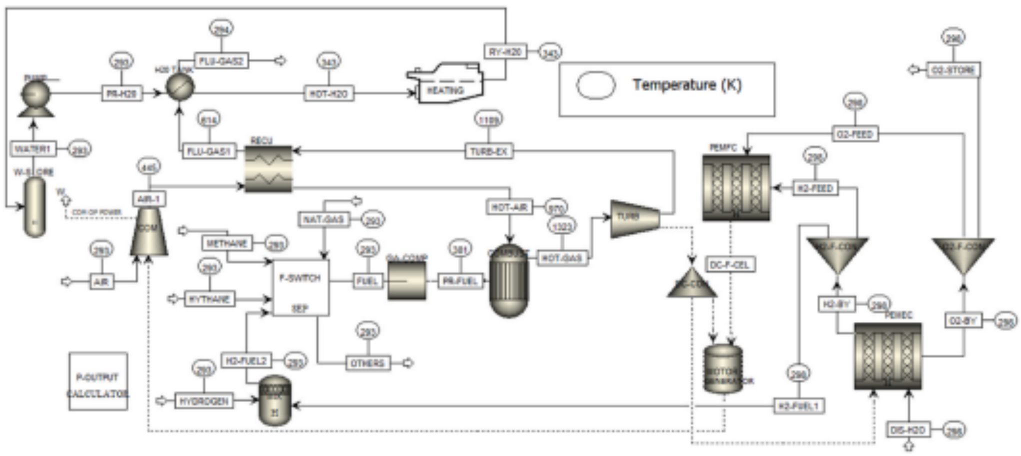

Fig. 4. Aspen Plus process diagram of MGT-CHP system coupled with PEM electrolyser and fuel cells.

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Table 3
Emission result of CC operating at 3 bar pressure and 1323.4 K temperature at 26.9 MJ/h and 5.5 kW energy output.

Fuel % NG	Fuel % CH_4	Fuel % H_2	Prod. CO_2 kg/h	Prod. H_2O kg/h	Prod. O_2 kg/h	Prod. N_2 kg/h	Prod. NOx kg/h	Air-to-fuel ratio
100			5	5.7	31.4	148.8	0.09	106:1
	100		5	5.7	31.3	148.8	0.09	106:1
	80	20	3.1	6.8	31.8	148.8	0.09	135:1
		100		8.5	32.5	148.8	0.095	252:1

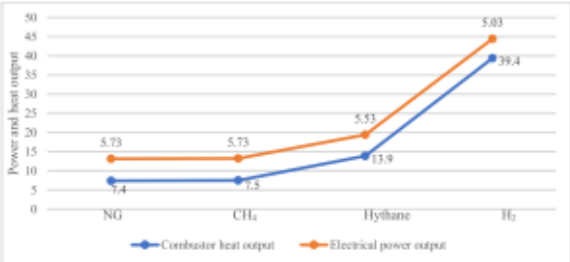

Fig. 5. Thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG, and CH_4.

3. Results and discussions

Table 3 illustrates the process simulation results. To reduce the percentage of CO_2 emissions in a micro-CHP system, a mixture of CH_4 and H_2 (hythane) should be used as the combustion fuel. Whereas the absence of CO_2 emissions from a micro-CHP system requires the burning of pure H_2 fuel in the combustion chamber. Using the same mass flow rate of hythane as NG, the heat output of the combustor was relatively higher, while smaller changes in heat output were observed in the burner operating with CH_4 as the fuel. Combustion of H_2 at the same mass flow rate as NG was extremely higher and increased the amount of NOx emissions and the overall efficiency. Thus, keeping the same fuel mass flow rate means that MGT combustors with larger bore diameters and lengths are needed for both hythane and H_2 to promote longer reactant residence time. To maintain the same combustor heat output for all fuels at a constant oxidant flow rate, the air-to-fuel ratio of 106:1 for NG and CH_4, 135:1 for hythane (80% CH_4 and 20% H_2) and 252:1 for H_2 were utilised. This approach reduced NOx formation and eliminated short reactant residence time which can lead to combustion outside the burner. Considering the mass flow rate of H_2 fuel into the combustor, the introduction of a small-scale renewable energy system such as a solar or wind energy system may be necessary to increase the H_2 by-product of the PEMEC. For example, utilising the power output of the developed model, a maximum of 40% of H_2 can be produced for hythane fuel. The deployment of both PEMEC and PEMFC has shown that it is possible to avoid the need to sell the generated electricity to the grid at a lower price and buy at a higher price to run the motor at 240,000 rpm during start-up. An increase in the power output of the model was possible by reducing the discharged turbine pressure since the downstream units are not pressure-dependent. For both the combustor and generator units operating at the listed air-to-fuel ratio in Table 3, a thermal energy output of 26.9 MJ/h and a net power output of 5.5 kW were recorded.

3.1. Fuel analysis of the simulated hybrid system

During the process simulation of the integrated system running on pure H_2, hythane, NG and CH_4, the combustion chamber outlet temperature is maintained at 1323.4 K. At the same mass flow rate of 0.5 g/s, the heat output of the combustion chamber was found to be 39.4 kW for pure H_2, which was much higher than 13.9 kW for hythane, 7.4 kW for NG, and 7.5 kW for CH_4 kW. The adiabatic flame temperature of H_2 is higher than hythane, NG and CH_4 resulting in higher heat production. However, H_2 produced a lower electrical output (5.03 kW) compared to hythane NG and CH_4 because of its low density. As shown in Table 4, the molar and mass enthalpy of the combustion chamber exhaust gas operating with pure H_2 had negative values compared to other fuels because the exothermic reaction releases more energy. By comparing the molar and mass entropy of the combustion chamber exit gases, H_2 has lower values because of its lightweight and movement flexibility [32]. The simulated system shows that the mass flow rate of H_2 and hythane can be reduced to achieve the same heat output of other fuels (NG and CH_4). However, reducing the mass flow rate of both fuels (H_2 and hythane) will further decrease the electrical power output of the MGT-CHP system. Thus, using the same mass flow rate of CH_4 for H_2 fuel to the MGT combustor, and recovering more heat for distilled H_2O production, more H_2 fuel can be produced via the electrolysis of H_2O in an application with less heat requirement. In this approach of substituting NG or CH_4 for pure H_2 fuel for more heat production, a larger micro combustor size with coolant addition such as steam or N_2 may be required to minimise thermal combustor wall stress and prevent exhaust gas exceeding 1323 K temperature. The simulated system achieved an efficiency of 96% for CHP and 82% for the electrolysis unit. Fig. 5 shows a thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG and CH_4. From the displayed graph, low-density and higher energy-density fuels produced more heat and less power output.

3.2. NOx emission analysis and model validation

The simulated hybrid MGT-electrolysers system with an output power of 5.5 kW requires larger H_2 and hythane combustors' size to operate smoothly as NG and CH_4 based MGT systems with low NOx formation. The result shows that NOx production was about 0.09 kg/h for all four fuels at lean combustion. For example, thermal NOx formation occurs at a reaction temperature above 1773.15 K [30].

Table 4
Comparison of combustor exit gas running on H_2, hythane, NG and CH_4 fuel at 0.5 g/s mass flow rate.

Properties	H_2	Hythane	NG	CH_4	Unit
Combustor heat output	39.4	13.9	7.4	7.5	kJ/s or kW
Electrical power output	5.03	5.53	5.73	5.73	kW
Molar Enthalpy of the combustor exit gas	−84.5	12106.3	15361.1	15304.5	kJ/kmol
Mass Enthalpy of the combustor exit gas	−3.1	429.6	539.6	537.7	kJ/kg
Molar Entropy of the combustor exit gas	38.4	41.1	41.7	41.7	kJ/kmol-K
Mass Entropy of the combustor exit gas	1.4	1459.5	1.5	1.5	kJ/kg-K
Enthalpy Flow of the combustor exit gas	−0.2	23	28.9	28.8	kJ/sec
Average	27.1	28.2	28.5	28.5	MW

However, CFD simulation software may be required to properly investigate the NOx amount on each fuel of the simulated system. Nonetheless, the addition of steam or N_2 may be required for H_2 combustion to control the NOx formation rate. The use of these renewable fuels such as H_2 and hythane has been found to provide efficient MGT performance and significantly reduce CO_2 and CO emissions. Designing flameless burners and maintaining H_2-controlled flame temperatures are two key points in the development of H_2 and hythane systems in this field (MGT-based micro-CHP system).

The simulated model is validated part by part with data listed in the literature. Comparing the MGT-CHP unit of this study with another MGT system installed at Staffordshire University, a marginal difference was recorded on combustors operating with H_2 and hythane fuels. The difference was attributed to the higher heat output of combustors operating with both fuels. For instance, NOx emissions <27 ppm (part per million) at 15% O_2, electrical power output of 3 kW, electrical efficiency of 16%, and a combined efficiency of >94% were reported for the MTT MGT-CHP system [33]. For this simulated system, higher electrical and lower thermal efficiencies were recorded. Higher electrical power output makes this model more suitable for small-scale units' where higher electrical energy is required. Comparing the efficiency of the PEMEC unit with Sapountzi et al. studied work, both studies achieved nearly the same efficiency. For example, PEMEC efficiency between 65%–82% was reported by Sapountzi et al. [34].

3.3. Environmental assessment and economic analysis

H_2 has many advantages over traditional fuels. The main advantage of H_2 and H_2-rich fuels in MGT is lower GHG emissions [35]. In recent years, H_2 and a mixture of H_2 and CH_4 (hythane) have been used in MGT systems [36]. This section presents the environmental analysis of renewable fuels such as H_2 and hythane with non-renewable fuels like NG or CH_4. The introduction of H_2 and hythane in the MGT-based micro-CHP system was found to reduce GHG emissions. The simulation results show that when producing the same power (i.e. 5.5 kW), H_2 releases zero CO_2 emission. While CO_2 emission of 3.1 kg/h for hythane, 5 kg/h for NG and CH_4 was seen. As current MGT-CHP systems use NG as fuel, GHG emissions and environmental pollution will continue to be on the rise. Although, NG-based MGT systems can still be used as a transitional fuel for coal and oil due to its lower CO_2 emissions, but not the most optimal energy solution [31]. To reduce carbon emissions and increase energy efficiency, H_2 stands out as one of the most potential energy carriers due to its CO_2-free and high energy density. Several countries, such as UK, Germany, Japan, USA, and China have proposed strategies to develop H_2-based energy technologies [37]. At the same time, H_2 research increased, including its production, storage and utilisation [38]. Connecting H_2 energy to MGT-CHP systems offers the possibility of even greater efficiency, reliability and lower emissions for residential and commercial applications. Therefore, a H_2-based MGT-CHP system has been considered a promising alternative to fossil fuel-based cogeneration systems in terms of efficiency improvement and reduction of carbon emissions [31].

The price of fuel is one of the most important parameters that has a direct relationship with the economic benefits of the MGT-CHP system operating with low-carbon fuels because it directly affects the operational cost. This section presents the economic analysis of H_2 and hythane with other fuels such as NG and CH_4. H_2 has a lot of potential for sustainable development but also has some disadvantages from an economic point of view because the economics of 100% H_2 dependence is still unknown and the higher cost of H_2 fuel reduces competitiveness [23]. The purchase price of H_2 is much higher compared to other fuels (hythane, NG and CH_4). For instance, green H_2 costs between $5.10/kg to 10.3/kg in contrast to grey H_2 (obtained from hydrocarbon reforming methods without carbon capture and storage (CCS) units) with a sales price of $1.89/kg [39]. In addition, H_2 production from NG will increase import by 30% [40]. In this regard, it would be beneficial to build H_2 production plants closer to CHP systems to mitigate storage and transportation costs and challenges [39,40]. By comparing H_2 and hythane from an economic perspective, it is more cost-beneficial to use hythane instead of 100% H_2 for MGT-CHP systems during the transition period. However, burring H_2 and CH_4 (hythane) at a ratio of 20:80 can reduce carbon emissions only by 7% [41]. In addition, electricity from the grid costs $0.5/kWh in the UK and $0.54/kWh in the USA [42]. While the feed-in tariff (FIT) is about $0.12/kWh or lower. By using produced electricity from the simulated system to produce H_2 rather than selling it at a cheaper rate to the grid, between 6 and 7% of GHG emissions and 43% end-user cost increase can be avoided. To achieve a successful H_2 economy, it is recommended to switch to more efficient and environmentally friendly H_2 production technologies.

4. Conclusion

A natural gas (NG), methane (CH_4), hythane ($H_2 + CH_4$) and hydrogen (H_2) fuelled MGT coupled with a PEM electrolyser and fuel cell units was process simulated as a combined system. The developed system produced H_2 for hythane fuel via the electrolysis of H_2O and electricity using a fuel cell system. By producing H_2 for hythane and electricity for electrical units, selling generated electricity to the grid at a cheaper rate and buying at a higher price were avoided. Low NOx emissions from both hythane and H_2 fuels showed that by burning any of these fuels with the addition of coolants such as H_2O in the combustor, the same NOx levels of NG-based MGT system can be achieved. Replacing NG with hythane reduced CO_2 emission by 7%, while the absence of CO_2 emission was attained from H_2 combustion. The findings also suggested the application of renewable solar or wind energy systems to the simulated system operating with H_2 fuel to increase the production rate. CFD simulation of MGT-CHP combustors operating with hythane and H_2 fuel with the addition of coolant was recommended to properly investigate NOx formation and thermal stress of the combustors' walls. An increase in the size of the MGT-CHP combustor operating with H_2 or hythane at the same fuel mass flow rate was also proposed to improve the reactant residence time and prevent combustion outside the combustor. Efficiency of 96% for CHP and 82% for electrolysis were achieved from the developed hybrid system.

Credit authorship contribution statement

Muhammad Asim Khan: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft. Linus Onwuemezie: Conceptualization, Methodology, Software, Validation, Review & Editing, Writing – Original Draft. Hamidreza Gohari Darabkhani: Methodology, Formal analysis, Investigation, Writing – Original Draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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