# 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.

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Micro-CHP systems, particularly when running on biofuels and hydrogen, provide excellent energy solutions for the future net zero buildings.

**Keywords**: *micro-Combined Heat and Power; micro-gas turbine; gas engine; Stirling engine; fuel cell; PESTLE risk analysis, Multi-Criteria Decision Analysis (MCDA)*

## 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 [1].

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 [1]. 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 [2]. 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 [3]. **Error! Reference source not found.** 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.

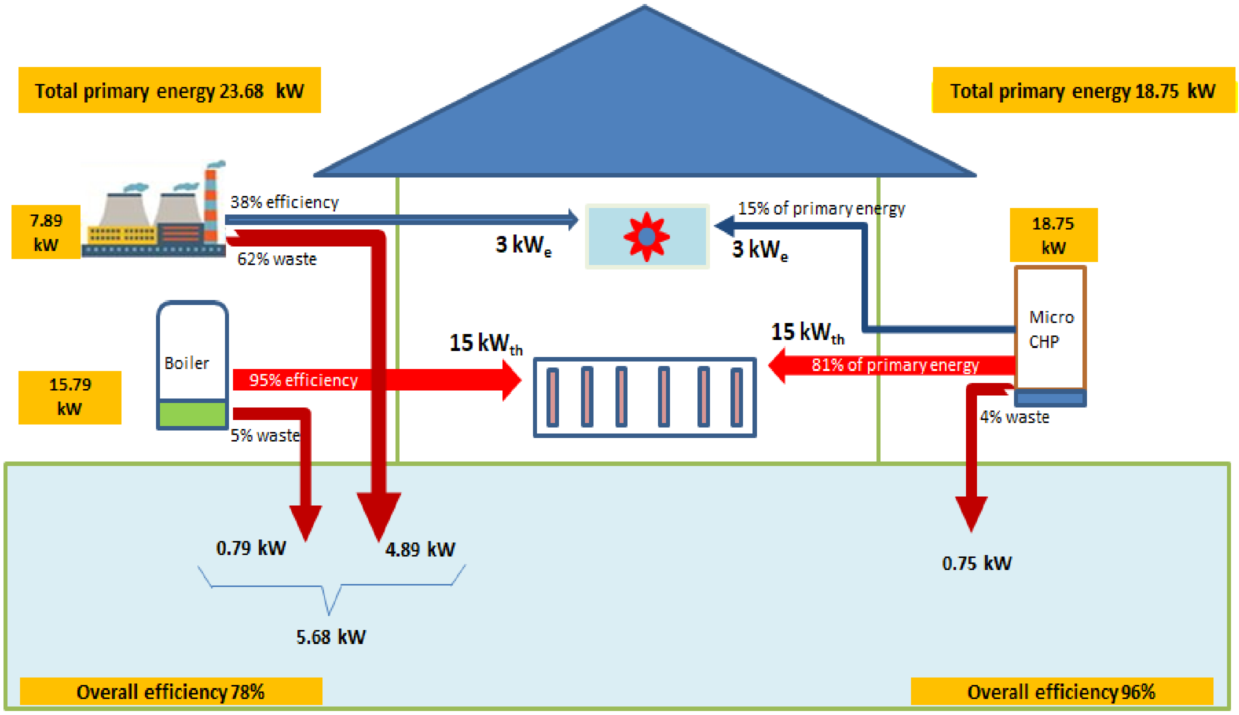

Figure 1: Conventional power and heat vs micro-combined heat and power generation, adapted from Progressing towards low carbon technologies for domestic use [4]

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 it's payback period is 1–3 years [5]. 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 [6].

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 ($\sum Q_{th}$) divided by the total fuel energy input ($Q_{fuel}$), as shown below:

$$\eta_0 = (W_e + \Sigma Q_{th}) / Q_{fuel} \quad (1)$$

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 [7]. The overall CHP efficiency is high and higher efficiency can effectively can reduce the emissions of NOx, greenhouse gas emissions, SOx, and volatile organic compounds as well [8].

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 [8]. They represent 94.1% of the total CHP worldwide installed capacity and are used mainly in industrial sites [9]. Sizes between 50 kWe to 1 MWe of CHP units are considered small-scale CHP [8] 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 [10]. 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.

**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 [11][12]. In the last decades, the development of micro-gas turbine systems 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 [13]. In today's market, micro-gas turbines are available in different sizes and cover a large range of power outputs [14]. 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 [15].

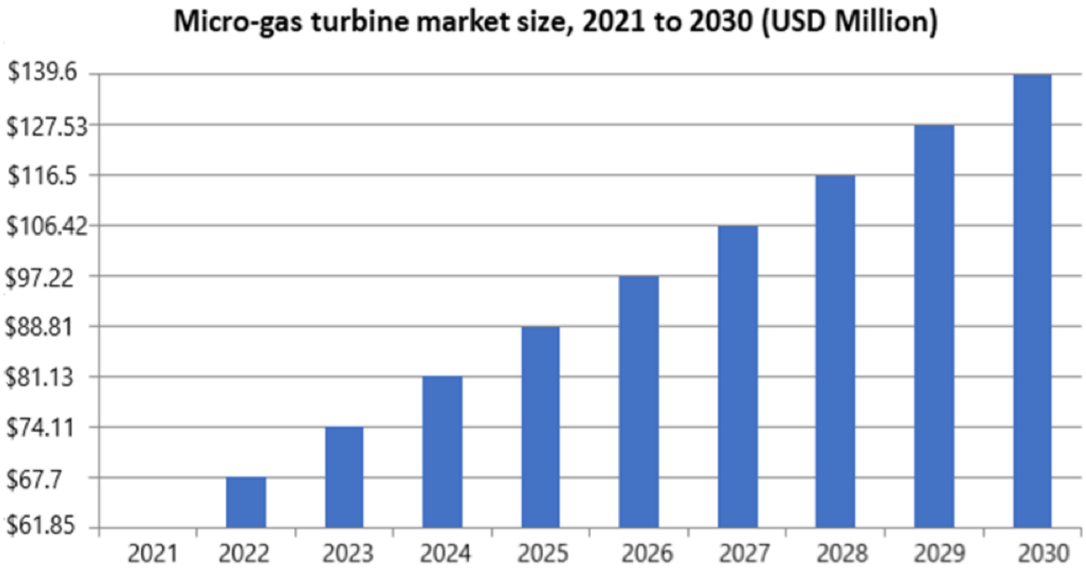

Figure 2: Micro-gas turbine market size, 2021 to 2030 (USD Million), adapted from [15]

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 [11]. 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. [13]. MGT has several important components which are Turbine, Combustor, Compressor, Electricity generator, and Recuperator [11]. **Error! Reference source not found.** shows the schematics of a recuperated micro-gas turbine engine.

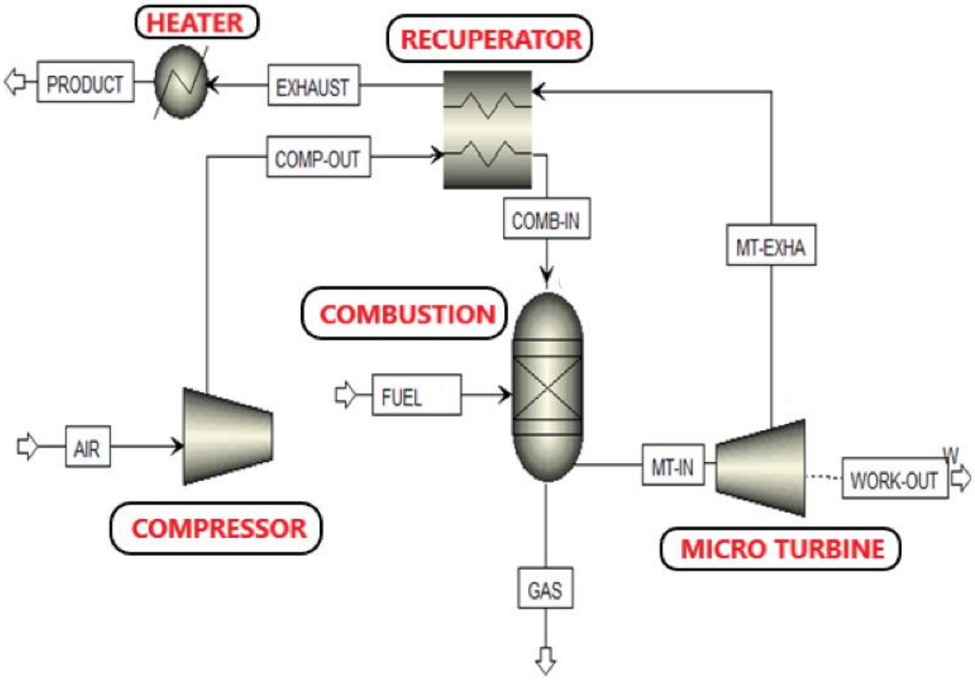

Figure 3: Schematics of micro-gas turbine engine [11][16]

Table 1 shows a list of commercially available MGT Micro- CHP systems with a power range of less than 50 kWe with their characteristics.

Table 1: Micro-gas turbine micro-CHP systems in the market

| **Brand** | **Model** | **Electrical Output (kW)** | **Electrical Efficiency (%)** | **Overall Efficiency (%)** | **Noise (dB)** | **Dimensions (mm) (HxWxD)** |
|---|---|---|---|---|---|---|
| MTT [17] | Enertwin | 3.2 | 16 | > 94 | 55 | 995 x 600 x 1170 |
| Capstone [18] | C30 | 30 | 26 | 90 | - | 1800x760.4x1500 |

The advantages and disadvantages of micro-gas turbines are presented in **Error! Reference source not found.**.

Table 2: Micro-gas turbine advantages and disadvantages [16][17][21][22][23][24][25]

| **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.<br>NOx (kg/MWhe) = 0.14–0.49<br>NOx 9-37 ppm @ 15% $O_2$<br>$CO_2$ (kg/MWhe) = 327<br>CO 40-80 ppm @15% $O_2$ | Requires high-speed bearings/generators and limitations on continuous on/off operations. |

### *2.2 Reciprocating Engines*

Reciprocating or piston engines are a well-established and widely used technology to generate power for several 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 [26]. 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 [27]. 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 [28]. **Error! Reference source not found.** shows a schematic of the reciprocating engine of a micro-CHP system.

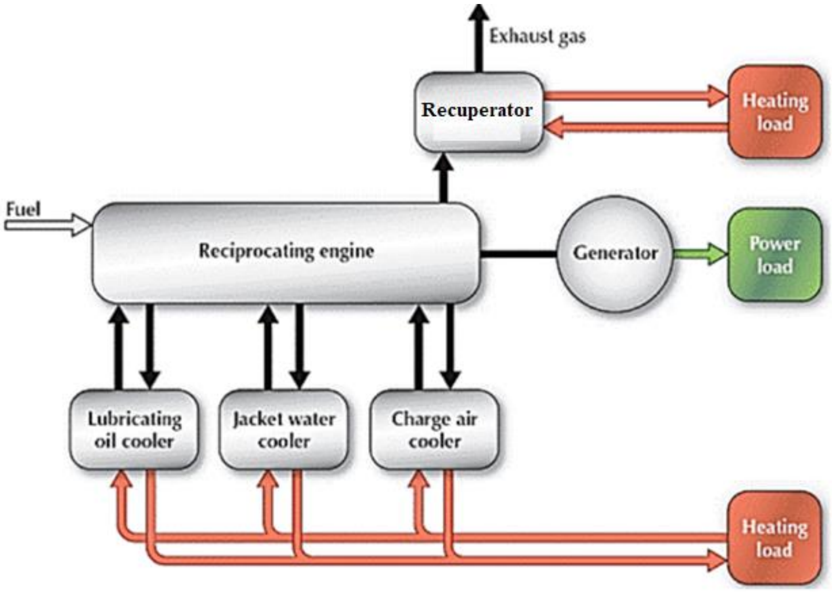

Figure 4: Schematic of reciprocating engine heat and power system [29]

Table 3 shows a list of commercially available reciprocating engines with their characteristics.

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) (WxDxH)** |
|---|---|---|---|---|---|---|---|---|
| Dachs [30] | G 5.5 | Natural gas | 5.5 | 14.8 | 25.6 / 28.4 | 93.9/104.2 | 48 | 720x1070x1270 |
| Dachs [30] | F 5.5 | LPG | 5.5 | 13.8 | 26.8 / 29.1 | 93.8 / 101.9 | 47 | 720x1070x1270 |
| Bosch [31] | CHP CE 12 NA | Natural gas | 6-12 | 13.75-27.5 | 30.2 | - | 56 | 882x1600x1263 |
| Bosch [31] | CHP CE 19 NA | Natural gas | 9.5-19 | 18-36 | 34 | - | 56 | 900x1800x1010 |
| Bosch [31] | CHP CE 50 NA | Natural gas | 25-50 | 40-80 | 33.8 | 87.9 | 65 | 960x2930x1730 |
| Bosch [31] | CHP CE 70 NA | Natural gas | 35-70 | 54.5-109 | 34.3 | 87.7 | 68 | 960x3275x1730 |
| EC POWER [32] | XRGI 6 | Gas (all qualities), propane, butane | 6 | 12.4 | 30.1 | 92.4 | 49 | 640x930x960 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EC POWER [32] | XRGI 9 | Gas (all qualities), propane, butane | 9 | 20.1 | 29.3 | 94.9 | 49 | 640x930x960 |
| EC POWER [32] | XRGI 15 | Gas (all qualities), propane, butane | 14.5 | 36.7 | 29.3 | - | 53 | 750x1120x1170 |
| EC POWER [32] | XRGI 20 | Gas (all qualities), propane, butane | 20 | 44.7 | 32.7 | - | 49 | 750x1120x1170 |
| EC POWER [32] | XRGI 25 | Gas (all qualities), propane, butane | 24 | 48 | 31 | 93 | - | 750x1120x1170 |
| SokraTherm [33] | FG 34 | Sewage gas/Biogas | 35 | 65 | 31.3 | 89.3 | 62 | 900x2200x1830 |
| EAW [34] | BHKWTyp EWK10S | Gasoline | 10 | 19 | 30.4 | 87.2 | - | 770x1600x2000 |
| Viallant [35] | Ecopower1.0 | Natural gas | 1 | 2.5 | 26.3 | 92 | - | - |

The advantages and disadvantages of reciprocating engines are presented in Table 4.

Table 4: Reciprocating engines: advantages and disadvantages [16]

| **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. |

### *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 [36][37].

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 [38]. Error! Reference source not found. shows a Stirling engine-based micro-CHP unit.

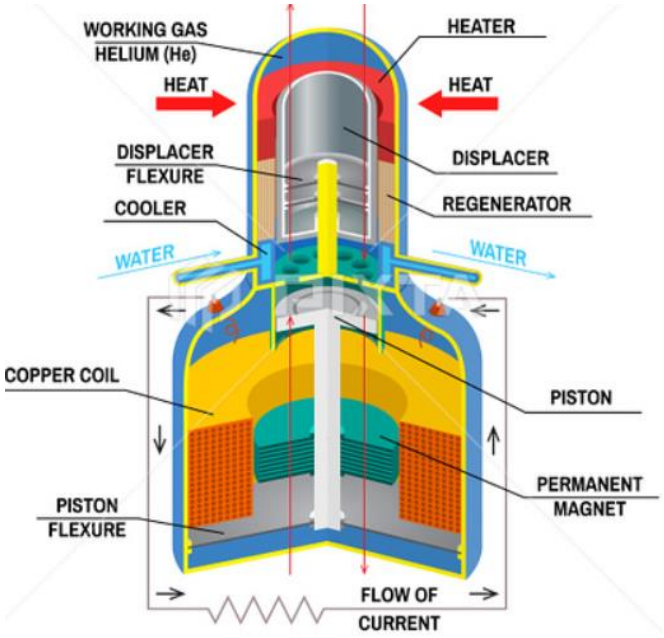

Figure 5: Stirling engine of micro-CHP system [39]

Error! Not a valid bookmark self-reference. shows a list of commercially available Stirling engines and their characteristics.

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) (WxDxH) |
|---|---|---|---|---|---|---|---|
| **Viessmman** [40] | Vitotwin 350F | 1 | 3.6-26 | 15 | 96 | - | - |
| **Baxi** [41] | Baxi ECOGEN | 1 | 7.7 | - | 90 | - | 450x426x950 |
| **Simons** [42] | QCHP-3500 | 3.5 | 14 | 20 | 103% LHV (Lower heating | 50 | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | value); 91% HHV | | |
| **Simons** [42] | QB-7500 | 7.5 | 30 | 20 | 103% LHV; 91% HHV | 50 | - |
| **Inspirit** [43] | Inspirit m-CHP | 6.4 | 15 | 15 | 90 | - | 630x650x850 |
| **Okofen** [44] | ÖkoFEN Smart_e | 0.6 | 9 | - | 90 | - | 1175x1150x1958 |

The advantages and disadvantages of Stirling engines are presented in Table 6.

Table 6: Stirling engines advantages and disadvantages [16]

| **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 fuel. | The heat transfer makes the engine far less responsive |

### *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. [16].

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 [16]. Figure 6 shows diagram of a fuel cell based micro-CHP system.

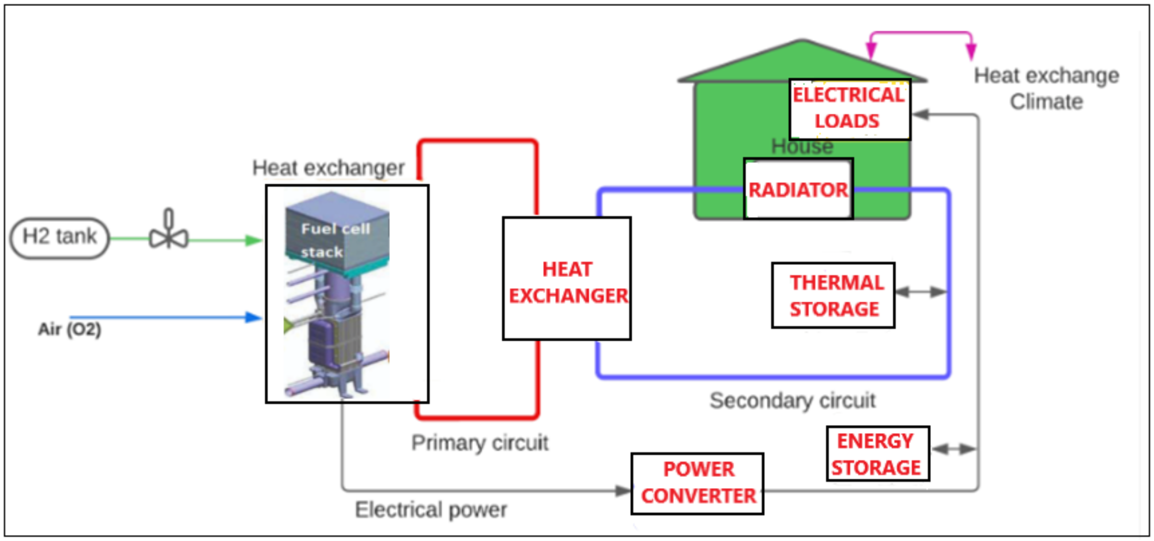

Figure 6: Fuel Cell based micro-CHP system diagram, adopted from [45]

The main technologies of the fuel cells that are most widely used for domestic applications are PEMFC and SOFC. **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 produced heat is also harnessed, their overall efficiency can even reach over 90% when converting fuel to energy [46]. Figure 7 shows a micro-CHP system with a flame-assisted SOFC.

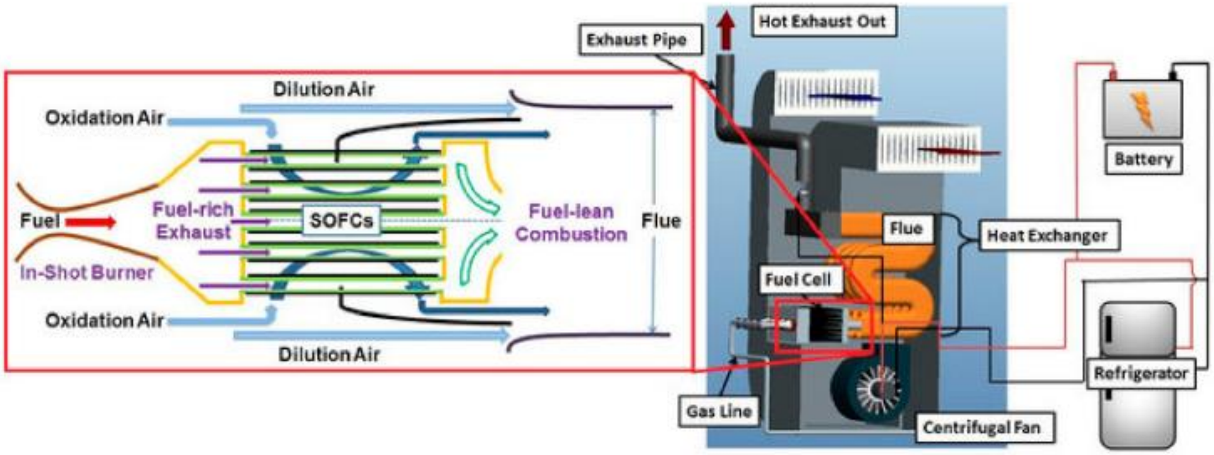

Figure 7: Micro-CHP system with a flame-assisted SOFC [47].

**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 [48]. Figure 8 shows a schematic illustration of a house powered by PEMFC.

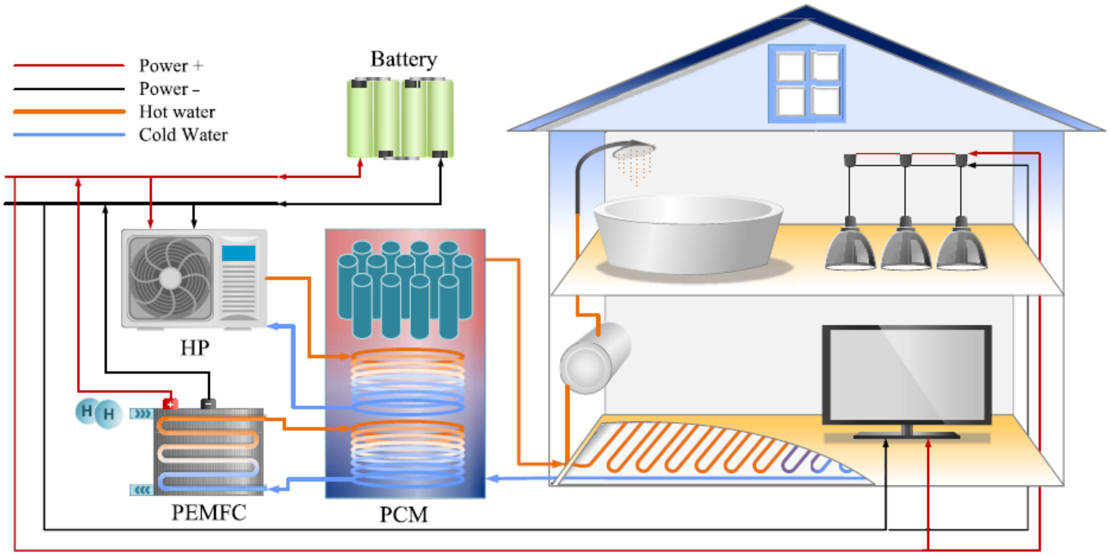

Figure 8: Schematic illustration of a house powered by PEMFC [49].

Table 7 shows a list of commercially available fuel cells with their characteristics.

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** [50] | BG-15 | SOFC | 1.5 | 55 | 88 | 550x800x1200 |
| **Elcore** [51] | Elcore 2400 | HTPEM technology | 0.3 | 32 | - | 600x550x1050 |
| **Elcore** [52] | Vitovalor 300-P from Viessmann | Low temperature PEM | 0.75 | 37 | > 90% (at trl <40 ° C) | 600x595x1932 |
| **Hexis** [53] | Galileo 1000 N | SOFC | 1 | 35 | 95 | 620x580x1640 |
| **Kd fuel cell** [54] | IRD Fuel Cell | PEM | 1.5 | - | 94 | - |
| **Baxiinnotech** [55] | Gamma 1.0 | PEM | 1 | 32 | >95 | 600x600x1600 |
| **Viessman** [56] | Vitovalor PT2 | PEM | 0.75 | 37 | 92 | 1200x595x1800 |

Table 8 shows the comparison of fuel cell applications, advantages, and disadvantages.

Table 8: Comparison of fuel cell applications, advantages, and disadvantages [16].

| Fuel Cell Types | Applications | Advantages | Disadvantages |
|---|---|---|---|
| Alkaline (AFC) | • Military<br>• Space | • Cathode reaction faster in alkaline electrolyte, leads to high performance<br>• Low-cost components | • Sensitive to CO2 in fuel and air<br>• Electrolyte management |
| Direct Methanol (DMFC) | • Backup power<br>• Portable power<br>• Military | • No need for reformer (catalyst separates H2 from liquid methanol)<br>• Low temperature | • Expensive catalysts<br>• Low-temperature waste heat |
| Phosphoric Acid (PAFC) | • Auxiliary power<br>• Electric utility<br>• Distributed generation | • Higher temperature enables CHP<br>• Increased tolerance to fuel impurities | • Platinum catalyst<br>• Startup time<br>• Low current and power |
| Proton Exchange Membrane (PEMFC) | • Backup power<br>• Portable power<br>• Distributed generation | • Solid electrolyte reduces corrosion & electrolyte management problems | • Expensive catalysts<br>• Sensitive to fuel impurities |

| | | | |
|---|---|---|---|
| | • Transportation<br>• Specialty vehicles | • Low temperature<br>• Quick startup | • Low-temperature waste heat |
| Molten Carbonate (MCFC) | • Auxiliary power<br>• Electric utility<br>• Distributed generation | • High efficiency<br>• Fuel flexibility<br>• Can use a variety of catalysts<br>• Suitable for CHP | • High-temperature corrosion and breakdown<br>• Long startup time<br>• Low power density |
| Solid Oxide (SOFC) | • Auxiliary power<br>• Electric utility<br>• Distributed generation | • High efficiency<br>• Fuel flexibility<br>• Can use a variety of catalysts<br>• Solid electrolyte<br>• Suitable for CHP & Combined heat, hydrogen, and power Hybrid/GT cycle | • High-temperature corrosion and breakdown of cell components<br>• High temperature operation requires a long startup time and limits |

The advantages and disadvantages of fuel cells are presented in Table 9.

Table 9: Fuel cells advantages and disadvantages [16]

| 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. |

## 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, 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 [57].

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 [16][24][58].

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 [59].

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" [10].

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.

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 ($/kW) | 900-1500 [24] | 3700 (£2937) [58] | 5000-6500 [16] | 1300-2500 [24] |
| S | The willingness to pay for fuel cells is higher than for the other technologies | | | | |
| T | Fuel | natural gas, biogas, LPG, sour gas, industrial waste gas, manufactured gas [16] | Any fuel [60] | hydrogen, natural gas, propane, methanol [16] | Natural gas, waste and sour gases, gasoline, kerosene, diesel, distillate fuel oil [24] |
| | Size ($m^3$) | 0.77 | 0.19 | 1.26 | 0.63 |
| | Overall CHP Efficiency | 86.7-94.9 [26][27] | 90-96 [34][37] | 88 - >95 [44][47] | 80 - >94 [16] [19] |
| | Power-to-heat ratio | 0.5-1.2 [16] | 0.1-0.4 [61] | 1-2 [16] | 0.5-0.7 [16] |
| | Part Load | Good [24] | Good [60] | Good [16] | Satisfied [24] |
| | Availability | 96-98 [16] | 99% [16] | 99% [16] | 98-99% [16] |

| | | | | | |
|---|---|---|---|---|---|
| | Start-up Time | 10 s [16] | 20 min – 1 hr [61] | 3 h-2 days [16] | 60 s [16] |
| 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 [24] | Low [60] | Low [61] | Moderate [24] |
| | $NO_x$ (kg/MWhe) | 0.99 [54] | 0.63 [54] | 0.011-0.016 [16] | 0.14-0.49 [16] |
| | $CO_2$ (lb/MWhe) | 650 [24] | 999.72 [16] | 980-998 [58] | 720 [24] |
| | 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. |

### *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.

Table 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 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. |

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 Discussion

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.

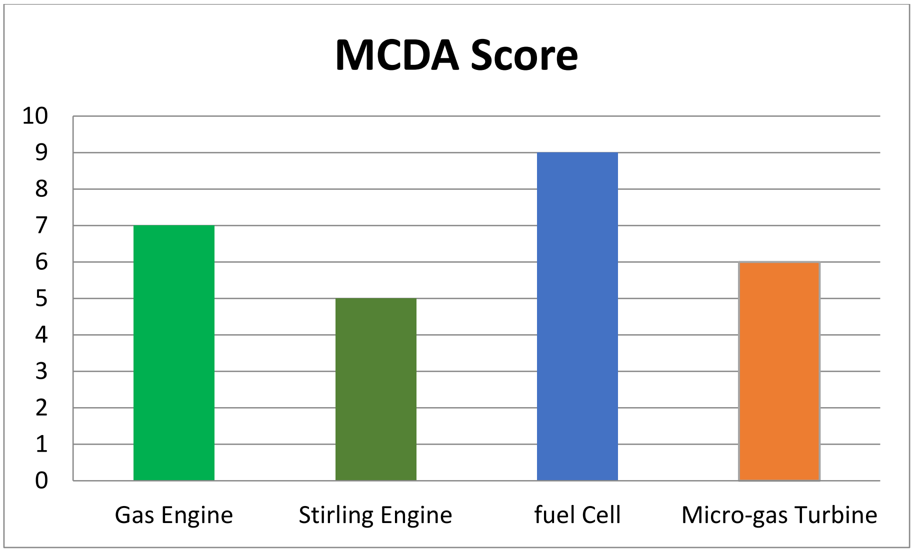

Figure 9: Results of the MCDA for different prime movers in micro-CHP systems

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, 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 residential 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.

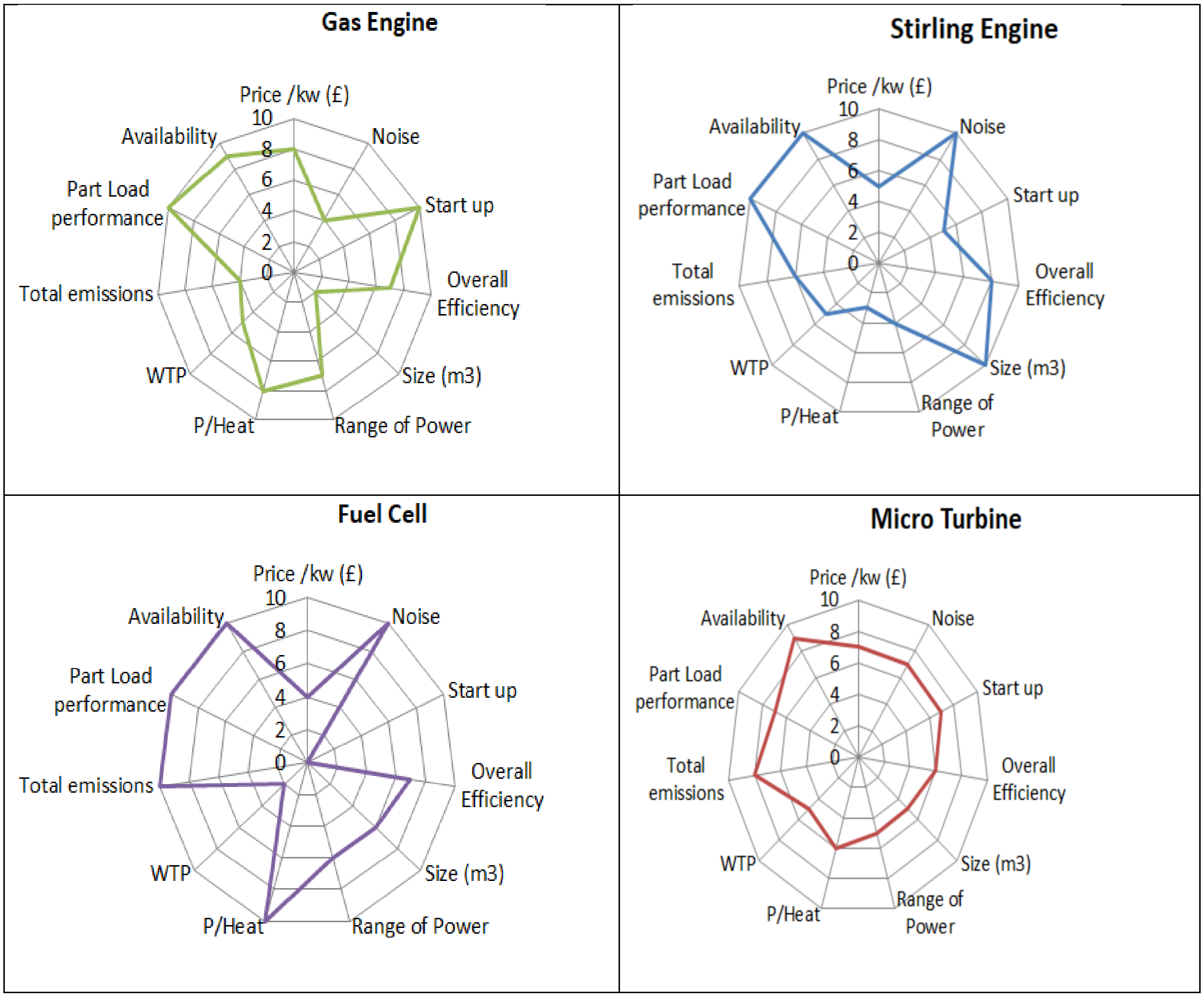

Figure 10: Characteristics of each prime mover according to the MCDA [16][24][26][27][34][37][44][47][54][58][60][61]

## 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, H2). 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 H2 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.

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