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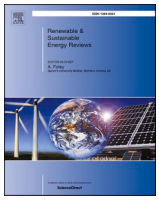

Techno-economic analysis of a fuel-cell driven integrated energy hub for decarbonising transportation

Samiran Samanta, Dibyendu Roy, Sumit Roy *, Andrew Smallbone, Anthony Paul Roskilly

Department of Engineering, Durham University, Durham, DH1 3LE, UK

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ABSTRACT

In this study an advanced integrated multigeneration energy hub is conceptualized combining solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), proton exchange membrane (PEM) electrolyser and methanol production unit. Using natural gas as a primary fuel input along with the renewable green excess electricity the proposed energy hub has a potential of generating electrical power, heat for district heat network, methanol for transportation use and oxygen for industry use. The thermodynamic analysis of the conceptualized multigeneration energy hub reveals that it can generate 322 kW electrical power, 766.4 kW heat, 0.024 kg/s methanol, and 0.0362 kg/s pure oxygen with 86.03% energy efficiency and 59.13% exergy efficiency. However, the economic analysis reveals that the annualized levelized cost of energy (LCOE) of the proposed energy hub is 0.06 £/kWh without having a battery storage and 0.065£/kWh with the battery storage system. The simple payback period of the proposed system is 2.16 year and 2.75 year without battery storage and with battery storage system, respectively. Two different case studies have been carried out by replacing the SOFC-MCFC combined unit with gas turbine (GT) combined with MCFC and GT combined with aqueous monoethanolamine (MEA) plant as two other alternative options for such multigeneration energy hub keeping other subunits unaltered. It has been found that the proposed system has the highest exergy efficiency, lowest levelized cost of energy (LCOE) and payback period followed by the GT-MCFC combined plant, and GT-MEA combined plant.

1. Introduction

The United Kingdom has set a goal of achieving net zero carbon emissions for the whole economy by 2050 [1]. To achieve this target, decarbonising road transport and domestic heating are the primary concerns. The transportation industry is the largest contributor to carbon emissions in the United Kingdom [2]. The Net Zero Strategy aims to phase out new gasoline and diesel automobiles and vans by 2030 and mandates that all vehicles have zero exhaust emissions by 2035 [3]. However, reducing emissions in the transportation sector will be challenging since technological advances will be countered by growing population and economic development, as well as increased demand for people, commodities, and services [4]. In this context, carbon capture and storage (CCS) has sparked a lot of attention for providing energy systems with decarbonization and flexibility [5]. However, CCS solutions for "diffuse" emissions like transportation and buildings, which account for 29% of global energy-based emissions, are less obvious [5]. Battery Electric Vehicles (BEVs) that run entirely on electricity and Fuel-Cell Electric Vehicles (FCEVs) that run on hydrogen are two of the most promising possibilities for lowering transportation's GHG emissions [6]. Beyond CCS, there is rising interest in carbon capture and utilization (CCU), an alternate use for captured CO_2 that might reduce emissions while simultaneously delivering useful commodities and energy system flexibility. However, most existing CCU routes are also uneconomical or have low technology-readiness levels (TRL), raising the question of whether alternative mitigation techniques should be deployed first [7]. CO_2 conversion into fuels using renewable energy has become one of the most popular CCU methods. Methanol is produced by reacting CO_2 extracted from point sources with hydrogen generated by renewable energy-powered water electrolysis. A fully integrated advanced energy system that could supply electricity or hydrogen to run either BEVs or FCEVs, as well as CCU producing e-methanol and other utility products, would help decarbonise the transport sector as well as other sectors, contributing to the UK's optimistic target of net zero emissions by 2050.

The solid oxide fuel cell (SOFC) is now emerging as a very energy efficient technique for power generation resulting from direct chemical conversion of fuel to electricity [8]. When compared to other types of fuel cells and other conventional energy conversion tools, the key

* Corresponding author.
E-mail address: sumit.roy@durham.ac.uk (S. Roy).

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Nomenclature

A	Area, m^2
AB	Air blower
ABR	Afterburner
AP	Air preheater
CAP	Individual component cost, £
CAPX	Total capital cost, £
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
El_{PEM}	Electrical energy input in electrolyser, kW
En	Energy flow rate, kW
F	Faraday's constant, C/mole
FB	Fuel Blower
FP	Fuel preheater
FUEL	Total fuel cost, £
GC	Gas combustor
GH	Gas preheater
GHG	Greenhouse gas
GT	Gas turbine
H	Hours of operation, hr
HRSG	Heat recovery steam generator
HWG	Hot water generator
I_{FC}	Fuel cell Current, Amp
I	Actual current flow, Amp
j	Current density, Amp/m^2
LHV	Lower heating value, kJ/kg
LCOE	Levelized cost of energy, £/kWh
$\dot{m}$	Mass flow rate, kg/s
M_{mol}	Molar mass, kg
MCFC	Molten carbonate fuel cell
MEA	manoethanolamine
MIX	Mixer
MS	Moisture Separator
N	Number of cells
OPEX	Total operational cost, £
P	Pressure, bar
PEME	Proton exchange Membrane Electrolyser
R	Area specific cell resistance, $\Omega.m^2$
REP	Total replacement cost, £
SOFC	Solid oxide fuel cell
T	Temperature, °C
UF	Fuel utilization factor
V	Voltage, Volt
W	Power, kW
y	Molar fraction

Greek symbols

η	Efficiency

Subscripts

DH	District heat network
i	ith number

advantages of employing SOFC include fuel flexibility, operation without noise pollution, minimal environmental pollutants, and fewer corrosion issues. Nevertheless, high-grade waste heat also comes out of SOFC as a by-product, which may be used in cogeneration, tri-generation, or multi-generation systems [9]. A wide range of study has already been conducted on the investigation and evaluation of various SOFC based energy systems for efficient clean power generation. Koo et al. [10] have carried out an exergy analysis of the SOFC–HCCI engine combined hybrid power generation system. Overall, 38% exergy efficiency of the hybrid system has been reported in the study. Wang et al. [11] have performed a techno-economic multi-objective optimization of a tri-generation system combining SOFC, a transcritical CO_2 cycle, a transcritical organic Rankine cycle (ORC), and a liquid natural gas (LNG) cold energy recovery system. The optimum exergy efficiency and cost of 56.1%, 16.82 $/h and 66.83%, 12.02 $/h have been reported for atmospheric SOFC system and pressurised SOFC system, respectively. Chitgar and Emadi [12] have carried out an exergonomic analysis of SOFC-GT based multi-generation system for producing electricity fresh water and hydrogen. It has been reported in the study that the proposed system generates 2.5 MW electrical power, 5.6 m3/hr water and 1.8 kg/h hydrogen with an exergy efficiency of 59.4% and a unit cost of products of 23.6 $/GJ. Wang et al. [13] have carried out energy, exergy and economy analysis of SOCF-GT-ORC integrated system for green power generation for ships. They have reported that 90% of the overall exergy destruction happens at the GT unit and cost destructions are mainly associated with the heat exchangers. Souza et al. [14] have carried out an economic assessment of a combined heat and power system producing hydrogen and electricity via steam reforming SOFC system. In the study hydrogen cost of 2.42–5.26 USD/kg and cost of energy over 0.269 USD/kWh have been reported. Zhu et al. [15] have performed a multi-objective optimization of a SOFC based combined cooling, heating and power (CCHP) system. It has been reported that the system at the optimum condition poses 75% CCHP efficiency, 52% electrical efficiency with a total annual cost of 410 k$. Hasanzadeh et al. [16] have performed a comparative energy and environmental analyses among conventional GT system, MCFC-GT system, and SOFC-GT system along with their performance optimization. Their results show that for a fixed 10 MW net output from each system SOFC-GT system is 26% more efficient and emits 39% less CO_2 compared to GT system. Whereas, for same power output the SOFC-GT system is 16% more efficient and emits 24% less CO_2 compared to MCFC-GT system.

Along with the efficient power generation from natural gas/methane fuel by using SOFC, carbon capture and utilization is on the cards for sustainable electric power generation with carbon footprint reduction. For decarbonising transportation or mobility, energy efficient carbon capture as well as reuse of the captured CO_2 via liquid fuel production would have been a good alternative option. The molten carbonate fuel cell (MCFC) has the exceptional feature of operating with CO_2-containing gas mixtures as an input gas stream [17]. Moreover, MCFC separates the CO_2 from its incoming cathode stream while simultaneously producing power simultaneously consuming natural gas/methane/hydrogen as fuel. It has also been shown that using MCFC, 90% or more CO_2 may be avoided from diverse flue gas sources while also providing additional electrical power [17]. Furthermore, being a high temperature fuel cell MCFC can easily be integrated with the different high temperature operating power generation devices like GT, SOFC etc [18]. Akrami et al. [19] have investigated bio energy based carbon capture system integrating biomass gasifier, conventional GT cycle, MCFC, ORC, and cryogenic separation unit. They have reported the proposed plant has a levelized cost of electricity of 55.76 USD/MWh which is comparatively higher than the conventional plant. Li et al. [20] have carried out a techno-economic analysis of novel polygeneration system for coal-to-methanol/power via carbon-capture using MCFC. They have reported that compared to existing conventional coal power plant the proposed system reduced the overall product cost by 1.68% and improved the exergy efficiency by 8.53%. Barckholtz et al. [17] have studied on the use of MCFC to capture CO_2 from cogeneration unit. They have shown that from a cogeneration system 87.6% of CO_2 can be avoided using amine based chemical capture which requires additional energy of 4.91 MJ/kg of CO_2. Whereas, from the same cogeneration

system 89.4% of CO_2 can be avoided using MCFC with an additional energy requirement of 1.37 MJ/kg of CO_2. Cooper et al. [21] have done a feasibility study for retrofitting MCFC with an existing coal fired power plant for CO_2 separation from the flue gas. Their results showed that the specific energy requirement for the MCFC based CO_2 capture system is of 1.41 MJ/kg CO_2 which is considerably less in comparison to the conventional Monoethanolamine (MEA) capture processes. Hosseini et al. [22] have performed an exergy assessment of a novel hybrid combined heat and power cycle (CHP) system combining MCFC, Steam Methane Reforming (SMR), Methanol Synthesis Process (MSP) with distillation process, GT cycle, Rankine cycle (RC), and ORC. It has been revealed that the proposed system generates 110.5 MW net electricity, 271.7 kg mol/h of 99.9% pure methanol, and 65398.7 kg mol/h hot water at 80 °C. The overall exergy and energy efficiencies of the proposed system were 58.4% and 83.7%, respectively.

Methanol synthesis is a very lucrative option for carbon capture and utilization pathways. The liquid fuel produced from the captured CO_2 gives a very good opportunity to decarbonise the energy system, especially if the hydrogen, utilized in methanol synthesis, comes from renewable energy sources. Lee et al. [23] have done the assessment of economic feasibility of methanol production using renewable hydrogen and captured CO_2. They have predicted that the for a 0.27 ton/day plant the unit methanol production cost is 1.42 $/kWh and for a 100 ton/day plant the cost is 0.48 $/kWh. Lonis et al. [24] have done a comparative study of two power-to-methanol integrated systems based on different electrolysis technology, i.e. alkaline electrolysers and the solid oxide electrolyser cells. Their results showed that the power to liquid efficiency is within the range of 0.57–0.71. Bos et al. [25] have done the techno-economic analysis of a renewable methanol production from captured CO_2 using H_2 produced from alkaline electrolysis process using wind energy. They have predicted 50% energy efficiency of a 100 MW wind power to methanol plant with an estimated methanol cost of 800 euro/ton. Su et al. [26] have carried a case study methanol production from hydrogenation of captured CO_2. Their study shows that the renewable methanol production process consumes 1.045 times more electricity than the traditional methanol production process. Whereas the traditional methanol production process consumes 2.5 times more thermal energy compared to the renewable methanol production method. Yousaf et al. [27] carried out a techno-economic assessment of an integrated system for methanol production via CO_2 hydrogenation utilizing hydrogen from solid oxide electrolyser (SOE). Their result shows that there is a 22.3% reduction in the cost of methanol production using SOE than using the alkaline water electrolyser. Dongliang et al. [28] have done a techno-economic analysis of a green hydrogen integration in the coal to methanol process. Their study shows that integration of green hydrogen process for methanol production resulted in 124.67% increase in methanol production, 10.52% increase in energy efficiency, 23.95% reduction in production cost. Battaglia et al. [29] have done techno-economic analysis of a methanol synthesis plant through hydrogenation of captured CO_2. They have reported that the production cost of methanol is 874 euro/ton.

The composition of Dublin's FREE NOW taxi fleet in 2021 is examined by Kinsella et al. [30], along with the potential decrease in emissions from electrifying the entire fleet. The data reveal that fully electrifying the fleet reduced carbon dioxide emissions by 77%. Wu et al. [31] carried out investigation to pinpoint the best route toward a sustainable bioenergy system, where the carbon produced in the fuel is balanced out by the GHG savings of the circular bio-based system. It offers a state-of-the-art analysis of several technologies and suggests a custom circular cascade bio-based system with anaerobic digestion as the primary platform, incorporating P2G systems for electro-fuels and pyrolysis of solid digestate for value-added pyrochar. Long et al. [32] carried out the investigation to compare the 2026 heat and transport sustainability criteria in the Sustainable Energy Directive (RED) recast by evaluating the life-cycle emissions from gasifying methanizing willow to produce renewable biomethane. The gasification of methane was shown to generally meet the criterion for reducing emissions for heat when converting from solely arable land. The conversion of arable land for the transportation end use resulted in the largest emission reduction of 97%. Gulagi et al. [33] examined a Philippine energy transition strategy that uses renewable resources. In 2050, direct and indirect electrification would increase efficiency across all sectors by more than 50% while maintaining annual investment levels between 20 and 55 billion euros. Heat would be provided by heat pumps, electrical heating, and solar thermal technology, while the transportation sector's energy needs would be met by direct power and synthetic fuels. Ramsebner et al. [34] examined the potential and difficulties connected with the transition from historically developed, isolated energy networks to renewable hybrid energy systems. Their study proposed the idea of an energy hub that would ignore any preexisting infrastructure and create a brand-new system from scratch, supplying various energy carriers with a single pipeline. We assert that such an approach should only be realised from the perspective of modelling as a virtual hub due to the related investment expense. When designing hybrid energy systems based on the pertinent information on consumer behaviour and available energy supply sources, an integrated modelling technique must be used.

Among various green hydrogen generation processes, the three most prominent electrolysis technologies are proton exchange membrane (PEM), alkaline (AL), and solid oxide (SOEC) electrolysis. PEM electrolysis is preferred in this study since it is regarded as the most promising approach for the future of power to gas technology [35]. PEM electrolysers have a compact design, a quick cold start time, a rapid system response, a wide operating range, a high current density, a high proton conductivity, the ability to work at low temperatures (60–80 °C), and a high output pressure (about 80 bar) [36]. Along with all these advantages there is also a huge opportunity to recover a high grade waste heat from the PEM electrolyser [36] that could be supplied to the district heat network.

It is clear from the preceding discussion that there are a very few studies on the integration of SOFC, MCFC for CO_2 separation, PEM electrolyser and methanol synthesis plant as a multi-generation energy hub which can produce electricity, e-methanol, oxygen, and useful heat for district heat network along with optional possibility of hydrogen generation. The United Nations established 17 sustainable development goals (SDGs) in 2015, with the aim of ensuring world peace and prosperity for both people and the planet by 2030 [37]. As a result of the goals' extensive interdependence, actions taken to accomplish one goal can sometimes also help accomplish some of the others. The SDGs' objectives include eradicating poverty and hunger as well as working to save the environment and advance human welfare and health. Supporting the requirements of the present and future generations is the UN's primary plan for protecting the environment. The UN prioritises resource preservation for future generations, with the backing of its 193 member nations. The SDGs are crucial for creating clean and inexpensive energy to save lives on land and at sea, which requires adopting tangible efforts because the world is in a climate emergency [38]. To lessen the effects of global warming, CCS/CCUS might be seen as an exceptionally dependable, secure, and sustainable option [39]. The aim of the study aligns with United Nations Sustainable Development Goal No. 7 "Affordable and Clean Energy". In order to contribute to the attainment of the SDGs, this study presents a thorough analysis of a fuel cell-based hybrid energy hub with several energy vectors and post-combustion carbon collection. With the goal of achieving the SDGs, this study is unlocking new opportunities for numerous engineering disciplines by incorporating sustainability into their projects. Additionally, the function of the CCUS in the circular economy to meet the SDGs relates to energy and the environment. Here, in this study detailed energy, exergy, and economic analyses have been carried out for an advanced hybrid multi-generation energy hub for decarbonising transport and heating network and energy grid. Fig. 1 shows the concept of fuel-cell driven integrated energy hub for decarbonising transport sector. The electricity and e-methanol can satisfy the need for

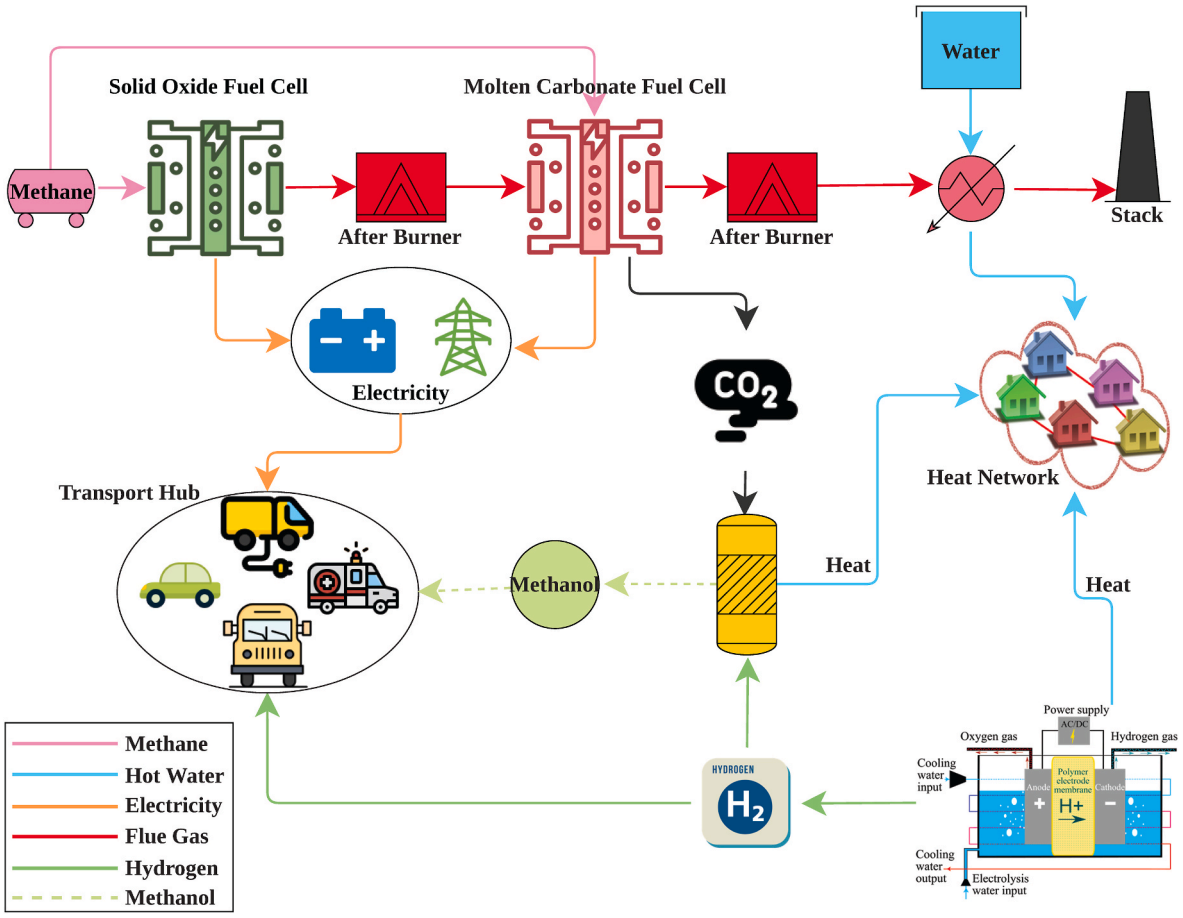

Fig. 1. Fuel-cell driven integrated energy hub for decarbonising transportation.

decarbonising the transportation sector as well as normal household energy need. The excess waste heat can help to decarbonise the heat network as well. It is always important to compare the performance of a system with competing technologies. Thus, in addition to the currently proposed system, two other case studies have also been conducted, one of which proposes the implementation of a conventional GT cycle in place of a SOFC and the other of which proposes the implementation of a conventional MEA-based chemical CO_2 capture process in place of an MCFC CO_2 separation. A comparative study among the proposed system and two other different case studies has been performed. The following are the significant contributions of the present work:

- Development of a novel hybrid advanced multi-generation energy hub concept incorporating SOFC, MCFC, PEM electrolyser, and a methanol synthesis plant.
- CO_2 separation of 90% or greater utilizing MCFC and e-methanol production.
- Thermodynamic and economic analyses of the proposed multi-generation energy hub.
- Techno-economic feasibility study of an advanced energy hub for decarbonising transport sector and district heat network simultaneously.
- Comparative feasibility study for better utilization of natural gas/methane via CCUS to decarbonise the transport sector.

2. System description

The proposed conceptualized system has been outlined in Fig. 2. The integrated system is comprised of a SOFC unit, MCFC unit, heat recovery steam generator (HRSG) unit for steam generation via waste heat recovery, a PEM electrolyser unit, and a methanol production unit. The SOFC unit consists of a SOFC module, mixer (MIX), an after burner (ABR), fuel preheater (FP1), air preheater (AP), fuel blower (FB), air blower (AB). The fuel blower sends the methane into the mixer (MIX), where it mixes with the steam. Then the gas-steam mixture gets pre-heated in the fuel preheater (FP1) before entering the cathode side of SOFC. Concurrently the air blower (AB) sends the fresh air, preheated in the air preheater, into the cathode side of SOFC. Both the anode and cathode exhausts are combusted in the afterburner (ABR). The after-combustion gas from the afterburner passes through the fuel pre-heater, air preheater and gas preheater (GH) before entering in the cathode side of MCFC stack. The MCFC unit consists of a MCFC module, gas Combustor (GC), fuel preheater (FP2), HRSG, gas preheater (GH), moisture separator (MS). Methane after mixing with steam passes through the fuel preheater and enters the anode side of the MCFC stack. The anode exhaust is burnt in the gas combustor (GC) in presence of pure oxygen supplied from the PEM electrolyser unit. The exhaust gas coming out of the gas combustor (GC) passes through the fuel preheater (FP2) preheating the methane-steam mixture, followed by the hot water generation at the hot water generator (HWG1) before entering the moisture separator (MS). From the moisture separator dry pure CO_2 is supplied into the methanol plant for methanol production. The MCFC cathode exhaust preheats the after-combustion gas from the SOFC unit at the gas preheater (GH), followed by superheated steam generation at the heat recovery steam generator (HRSG), and hot water generation at the second hot water generator (HWG2) before going into the atmosphere. The produced hot water is proposed to be sold for district heat network. The hydrogen required for the methanol production has been supplied from a PEM electrolyser unit. Excess renewable electricity of 1 MW from the wind power generation is proposed to be utilized to run the

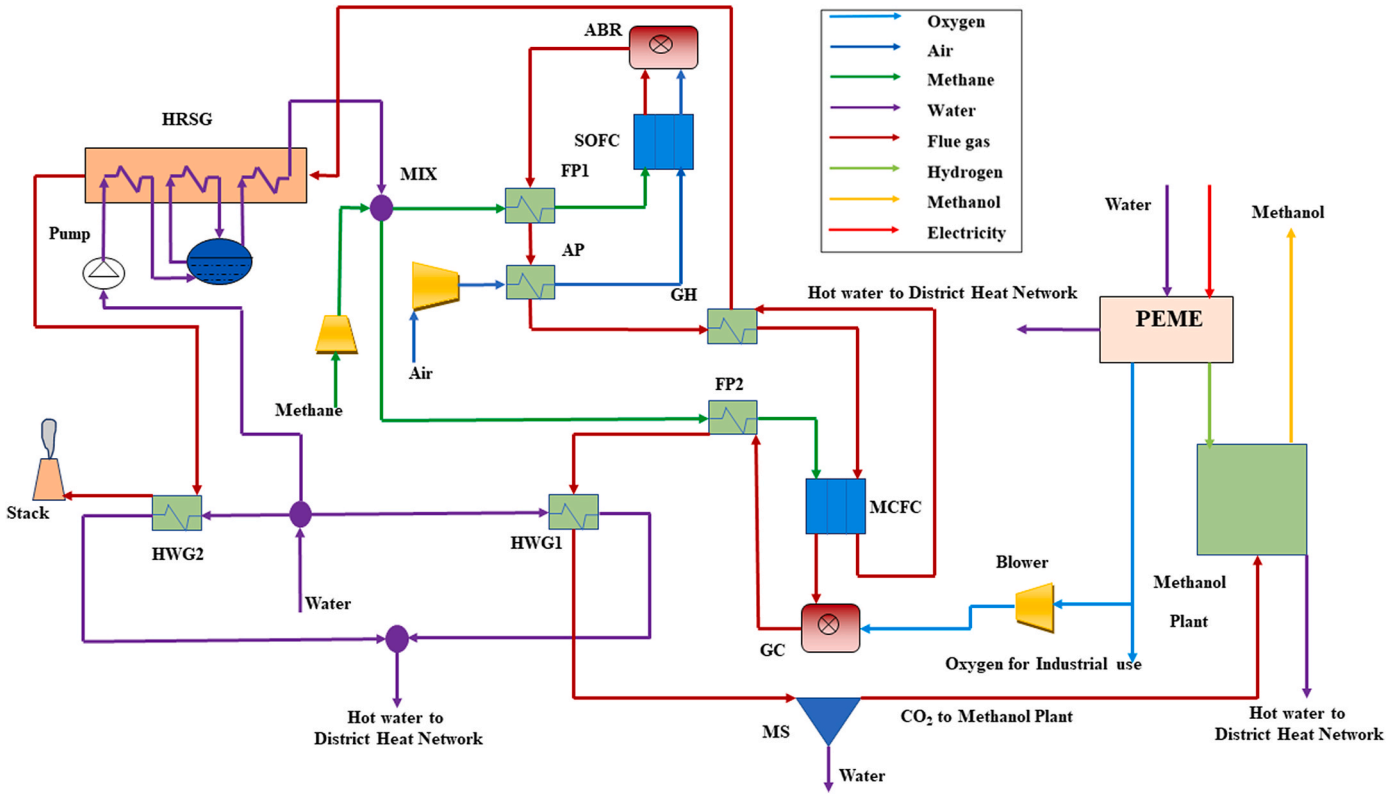

Fig. 2. Layout of the proposed SOFC-MCFC-Methanol system.

electrolyser unit. The detailed design of the electrolyser unit can be found in Ref. [36]. Along with the hydrogen, pure oxygen and waste heat are produced from the electrolyser unit. The waste heat from the PEM unit is also proposed to be sold for district heat network. After fulfilling the demand of pure oxygen required in the gas combustor (GC) of MCFC unit there are excess pure oxygen available which is generated from the electrolyser unit. This excess oxygen is one of the by-products of this proposed system which would be sold for industrial use. The detailed design of the methanol plant has been discussed later in section 3.4. The hydrogen from electrolyser unit and the pure CO_2 from the MCFC unit are get compressed before going to the reactors of the methanol plant to produce methanol. The compressor negative work is supplied from the net power generated from the SOFC and MCFC unit. The methanol plant has several intermediate heat addition and heat rejection processes. Overall, the methanol plant produces a good amount of waste heat which is also proposed to be sold for district heat network. Finally, the proposed conceptualized multigeneration energy system can produce net electrical work, heat to district heat network, pure oxygen for industrial use, methanol to be used as liquid fuel, and hydrogen as well as another alternative option.

3. System development and analysis

3.1. Solid oxide fuel cell for power generation

The solid oxide fuel cell (SOFC) is a high temperature fuel cell which generally operates at 650–1000 °C [8]. SOFCs are highly efficient electrochemical devices which consume hydrogen or methane of natural gas as fuel and converts into electricity without direct combustion of fuel. Among different types of SOFC, an internally reformed type SOFC is considered here for this study. For the analysis a lumped volume zero-dimensional approach has been followed to do the mass and energy balances at the SOFC unit. Thermo-physical properties and chemical composition of the fuel and air at the fuel cell inlet, fuel utilization factor, oxidant utilization factor, cell area, cell temperature, cell voltage are assigned as inputs to the model. After that the model estimates the temperature and pressure at the fuel cell outlet, electrical output, and the composition of the outgoing anode and cathode exhausts through overall energy balance at the fuel cell.

Current flow though SOFC can be determined by the following relation [11].

$$I_{FC} = \frac{\dot{m}_{anode,in} \times \left(y_{H_2} + y_{CO} + y_{CH_4}\right) \times 2 \times F}{M_{mol,anode}} \tag{1}$$

where, $y_{H_2}, y_{CO}, y_{CH_4}$ are the molar concentrations of H_2, CO and CH_4 at the inlet; F is the Faraday constant; $M_{mol,anode}$ is the mol mass of anode gas and $\dot{m}_{anode,in}$ is the anode inlet mass flow rate.

The fuel utilization factor (UF) denotes the ratio of actual to maximum feasible conversion of fuel into power and it is represented by the following equation

$$UF = \frac{I}{I_{FC}} \tag{2}$$

where, I denote actual current flow.

The SOFC voltage can be estimated by the following relation [11].

$$V_{SOFC} = \frac{\Delta G}{2F} + \frac{RT_{SOFC}}{2F} ln\left(\frac{y_{O_2}^{0.5} \times y_{H_2}}{y_{H_2O}} \times P_{SOFC}^{0.5}\right) - j \times R_{SOFC} \tag{3}$$

where, R_{SOFC} is the resistance for SOFC; ΔG is the standard Gibbs free energy; T_{SOFC} is operating temperature of SOFC; P_{SOFC} is the operating cell pressure; y_{H_2O} represents mole fraction of H_2O; y_{O_2} is the mole fraction of O_2, and R is the universal gas constant.

The power generated by SOFC module can be estimated as follows [11].

$$\dot{W}_{SOFC} = N_{SOFC} \times j \times A_{SOFC} \times V_{SOFC} \times \eta_{inv} \tag{4}$$

where, N_{SOFC} is the number of cells; j is the current density; A_{SOFC} is the cell area; η_{inv} is the efficiency of inverter.

3.2. CO_2 separation and capture using molten carbonate fuel cell

Just like the SOFC, MCFC is also another type of high temperature fuel cell which generally operates at 600–700 °C [17]. For operating MCFC hydrogen or hydrogen containing gas is feed as fuel into the anode channel. Hydrogen can be fed directly or can be generated through the reforming reaction (externally/internally). Here and internal reforming type MCFC has been proposed to be utilized. In the cathode channel gas mixture having CO_2 and O_2 such as after combustion gas or flue gas or exhaust gas is fed. In presence of oxygen and at very high temperature carbonate ion forms in the cathode side of MCFC. At the same time at very high temperature the electrolyte (mixture of carbonate salts of sodium, potassium and lithium) forms a molten salt forming carbonate ions that allows the transfer of carbonate ions from cathode to anode channel of MCFC. Reaching at the anode, the carbonate ions combine with the hydrogen producing carbon dioxide and steam. During this electrochemical reaction electrical power is also generated. As a result, when a flue gas is fed into the MCFC CO_2 is separated from the flue gas easily and power is produced as well. The operating principle is depicted here in Fig. 3.

Like the simulation of SOFC unit, a lumped volume zero-dimensional approach has been followed to do the mass and energy balances simulation at the MCFC unit.

All the thermo-physical properties of the reactant at MCFC inlet, chemical composition, mass flow rate, fuel utilization factor, CO_2 utilization factor, cell voltage, current densities are given as inputs for the simulation purpose. From the simulation the power output, chemical composition of the MCFC anode and cathode exhausts, pressure and temperature at the MCFC outlet are estimated. The cell voltage of MCFC is estimated using the reversible Nernst potential equation [17] and is given as follows

$$V_{MCFC} = \frac{\Delta G}{2F} + \frac{RT_{MCFC}}{2F} ln\left(\frac{y_{O_2,cathode}^{0.5} \times y_{H_2,anode} \times y_{CO_2,cathode}}{y_{H_2O,anode} \times y_{CO_2,anode}} \times P_{MCFC}^{0.5}\right) - j \times R_{MCFC} \quad (5)$$

where, R_{MCFC} is the resistance for MCFC; ΔG is the standard Gibbs free energy; T_{MCFC} is operating temperature of MCFC P_{MCFC} is the operating cell pressure; $y_{H_2,anode}$ represents mole fraction of H_2 in the anode channel; $y_{O_{2,cathode}}$ is the mole fraction of O_2 in the cathode channel; $y_{CO_2,anode}$ is the mole fraction of CO_2 in anode channel; $y_{CO_2,cathode}$ is the mole fraction of CO_2 in cathode channel and R is the universal gas constant.

The power generated by MCFC module can be estimated as follows [18].

$$\dot{W}_{MCFC} = N_{MCFC} \times j \times A_{MCFC} \times V_{MCFC} \times \eta_{inverter} \quad (6)$$

where, N_{MCFC} is the number of cells; j is the current density; A_{MCFC} is the cell area; $\eta_{inverter}$ is the efficiency of inverter.

3.3. Hydrogen production using PEM electrolyser

In this study the captured CO_2 is proposed to be utilized for methanol production by using green renewable hydrogen in a methanol production plant. A 1 MW PEM electrolyser is proposed to be used for producing green hydrogen via water electrolysis using excess renewable energy produced from offshore windmills. Along with the hydrogen, pure oxygen and useful amount of heat have been produced from the PEM unit as the by-products. The produced oxygen is proposed to sell in the market for industrial use. Whereas the useful amount the heat is proposed to feed in the district heat network. This makes the proposed integrated system as a multi-generation energy hub. The detailed modelling of the PEM unit was conducted in the previous work of Burrin et al. [36]. The same methodology has been repeated here for the modelling of PEM as an individual and coupled with the modelling for the performance simulation and analysis of the whole integrated system.

3.4. Hydrogenation of CO_2 to methanol

Since fossil fuels are depleting and the impact of carbon dioxide (CO_2) build-up in the environment is becoming more apparent, CO_2 reuse is a critical issue. CO_2 hydrogenation could be a solution. To this end a model was developed in Aspen Plus software package to hydrogenate the CO_2 captured using molten carbonate fuel cell and H_2 produced by water electrolysis using the PEM electrolyser. The process is depicted in Fig. 4.

Methanol is produced by the exothermic process (Equation (7)), where 3 mol of hydrogen react with 1 mol of carbon dioxide to produce 1 mol of methanol and 1 mol of water. But entire amount of CO_2 is not hydrogenated directly. Some is subjected to endothermic reverse water-gas-shift reaction (Equation (8)), also known as RWGS, which transforms 1 mol CO_2 and 1 mol H_2 into 1 mol of CO and 1 mol of H_2O. The hydrogenation of the carbon monoxide produced results in the creation of methanol (Equation (9)), which is also an exothermic reaction. The

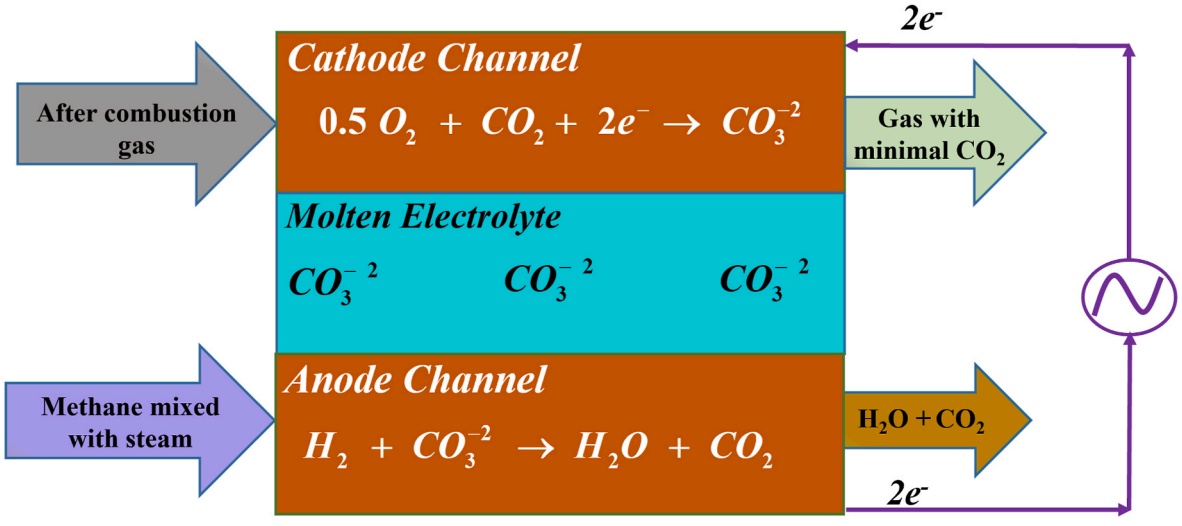

Fig. 3. Schematic representation of Molten carbonate fuel cell working principle.

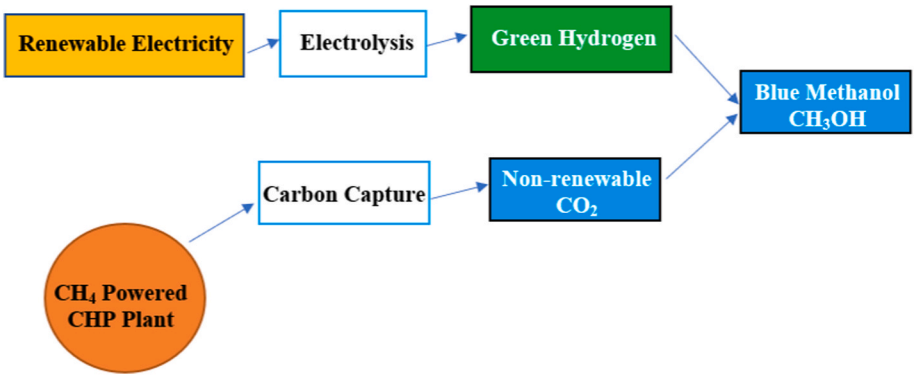

Fig. 4. Methanol generation from captured CO_2 and H_2 produced by electrolysis.

catalytic reaction was carried out in a fixed-bed catalytic reactor at 285 °C using Cu as the catalyst, which is in accordance with the literature [26,40–42].

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad (7)$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad (8)$$

$$CO + 2H_2 \leftrightarrow CH_3OH \quad (9)$$

For the production of methanol, 0.0052 kg/s of H_2 at a temperature of 25 °C and a pressure of 30 bar and 0.03328 kg/s of CO_2 at a temperature of 25 °C and at atmospheric pressure were considered. The CO_2 to H_2 ratio is consistent with literature [26,40]. The methane powered combined heat and power plant and the PEM electrolyser were scaled accordingly to produce the required amount of CO_2 and H_2 simultaneously. The methanol produced from the methanol generation plant was 0.023997997 kg/s and was 99.9976% pure. This produced methanol can be directly used or can be blended with conventional fuels for transport applications. This will improve performance of the engines resulting in a better fuel economy along with significant reduction in emissions [43–45].

3.5. Thermodynamic performance assessment

For the thermodynamic performance evaluation of the proposed multigeneration energy hub the first law and second law efficiencies have been estimated. The input parameters used for the simulation of PEM electrolyser unit are in line with the [36]. The input parameters for the simulation of SOFC block has been referred from the [9,10,46]. The design and operating parameters for the MCFC block operation has been referred from the [17,18]. The design and operating parameters are in line with the [41,42]. All the input parameters for the overall plant performance are tabulated in Table 1.

For the energy efficiency estimation, the total energy input is calculated first. There are two energy input into this system, one is the fuel energy input and other is the renewable electrical energy input into the PEM electrolyser unit. The total energy input is estimated by the following equation.

$$En_{total} = \dot{m}_{fuel} \times LHV_{fuel} + El_{PEM} \quad (10)$$

where $\dot{m}_{fuel}$ represents the fuel supply in kg/s, LHV_{fuel} represents the lower heating value of the fuel in kJ/kg, and El_{PEM} represents the electrical input into the PEM electrolyser.

Form the proposed multigeneration energy hub Electrical power, heat, methanol, and oxygen are produced as different outputs.

The net total power output (W_{net}) is estimated by the following equation.

$$W_{net} = W_{SOFC} + W_{MCFC} - W_{auxiliary} \quad (11)$$

Table 1
Input parameters for technical analysis.

Components	Parameters	Values	Units
PEM electrolyser Unit	Output Pressure	30	bar
	Operating Temperature	65	°C
	Input electricity	1	MW
	Water intake	50.64	kg/s
	Exit temperature	30	°C
MCFC unit	Current density	1500	A/m^2
	Total area	57	m^2
	Stack temperature	650	°C
	CO_2 utilization factor	0.8	–
	Fuel utilization factor	0.85	–
	Oxygen utilization factor	0.18	–
	DC-AC Conversion efficiency	98	%
SOFC unit	Current density	1500	A/m^2
	Total area	230	m^2
	Resistance	2.8×10^{-05}	Ω.m^2
	Stack temperature	750	°C
	Fuel utilization factor	0.85	
	Oxygen utilization factor	0.18	
	DC-AC Conversion efficiency	98	%
Methanol production unit	H_2 flow rate	0.0052	kg/s
	H_2 initial temperature	25	°C
	H_2 initial pressure	30	bar
	H_2 final pressure	96	bar
	CO_2 initial temperature	25	°C
	CO_2 initial pressure	1.013	bar
	CO_2 final pressure	96	bar
	Isentropic efficiency of compression	85	%

where W_{SOFC} and W_{MCFC} represent the power output from the SOFC and MCFC, respectively. $W_{auxiliary}$ represents the total auxiliary power consumed in the integrated system. The total auxiliary power comprised of all the negative power consumed by the water pump, air compressor, fuel compressor, CO_2 compressor used at the methanol plant etc.

Waste heat is produced from the SOFC and MCFC combined unit. Some waste heat is generated from the PEM electrolyser unit and a substantial amount of waste heat is generated at the methanol plant. All these waste heats are combined to generate hot water at 75 °C to supply for local district heat network. The total heat generated from the integrated system is estimated as follows

$$Q_{DH,\text{total}} = Q_{Fuel\ Cell} + Q_{PEM} + Q_{Methanol\ \text{Plant}} \quad (12)$$

The energy associated with the produced methanol is estimated from the following equation

$$En_{Methanol} = \dot{m}_{Methanol} \times LHV_{Methanol} \quad (13)$$

where $\dot{m}_{Methanol}$ represents the amount of generated methanol in kg/s, $LHV_{Methanol}$ represents the lower heating value of methanol in kJ/kg.

There is no energy generation associated with the produced oxygen at the PEM electrolyser unit. So, finally the first law efficiency of the proposed multigeneration energy hub is estimated as follows

$$\eta_{first\ law} = \frac{W_{net} + Q_{DH,total} + En_{Methanol}}{En_{total}} \tag{14}$$

the physical and chemical exergies. The exergy of the heat supplied to the district heat network is estimated as follows

$$(Exergy)_{waste\ heat} = Q_{DH,total} \times \left(1 - \frac{T_{ambinet}}{T_{hot\ water}}\right) \tag{16}$$

Finally, the second law efficiency of the proposed multigeneration energy hub is estimated by the following equation

$$\eta_{\text{sec ond law}} = \frac{\left[\begin{array}{l} W_{net} + (Exergy)_{waste\ heat} \\ +\dot{m}_{methanol} \times (Specific\ Exergy)_{methanol} + \dot{m}_{oxygen} \times (Specific\ Exergy)_{oxygen} \end{array}\right]}{(Inlet\ Exergy)_{total}} \tag{17}$$

For the second law analysis of the system, first the specific exergy of the fuel followed by total exergy input through fuel have been estimated. The specific exergy of any material flow is a combination of its physical exergy and chemical exergy. There are two input exergies into this proposed system. One is through the fuel input and other is direct electrical power (itself an exergy). The total exergy input into the integrated system has been estimated as follows

$$(Inlet\ Exergy)_{total} = \dot{m}_{fuel} \times (Specific\ Exergy)_{fuel} + El_{PEM} \tag{15}$$

The output exergies of the proposed system are the electrical power output, the exergy associated with the waste heat supplied to the district heat network, the exergy associated with the methanol produced and the exergy value of the oxygen produced from the PEM electrolyser unit. The exergy values associated with the methanol and the oxygen are estimated from their respective specific exergy values combining both

The detailed inflow and outflow and an overall exergy balance sheet of the multigeneration energy hub is portrayed in Fig. 5.

Table 2
Thermodynamic performance of the proposed plant.

Parameter	Numerical Value	Units
Fuel Input	0.014	kg/s
Electricity Input	1000	kW
Net power Output	322	kW
Net Heat supply to district Heat network	766.4	kW
Methanol Produced	0.024	kg/s
Oxygen produced	0.0361	kg/s
First Law Efficiency	86.024	%
Second law Efficiency	59.125	%

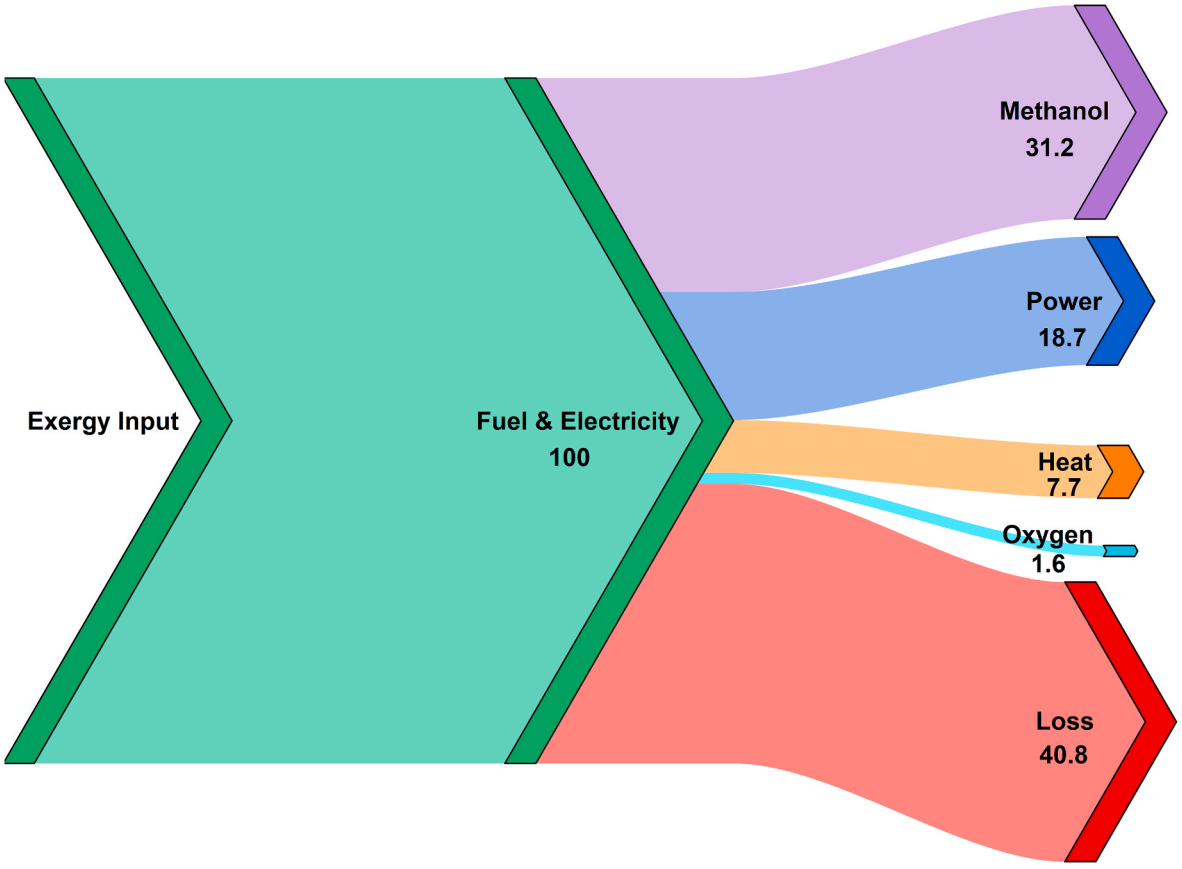

Fig. 5. Exergy flow of the system.

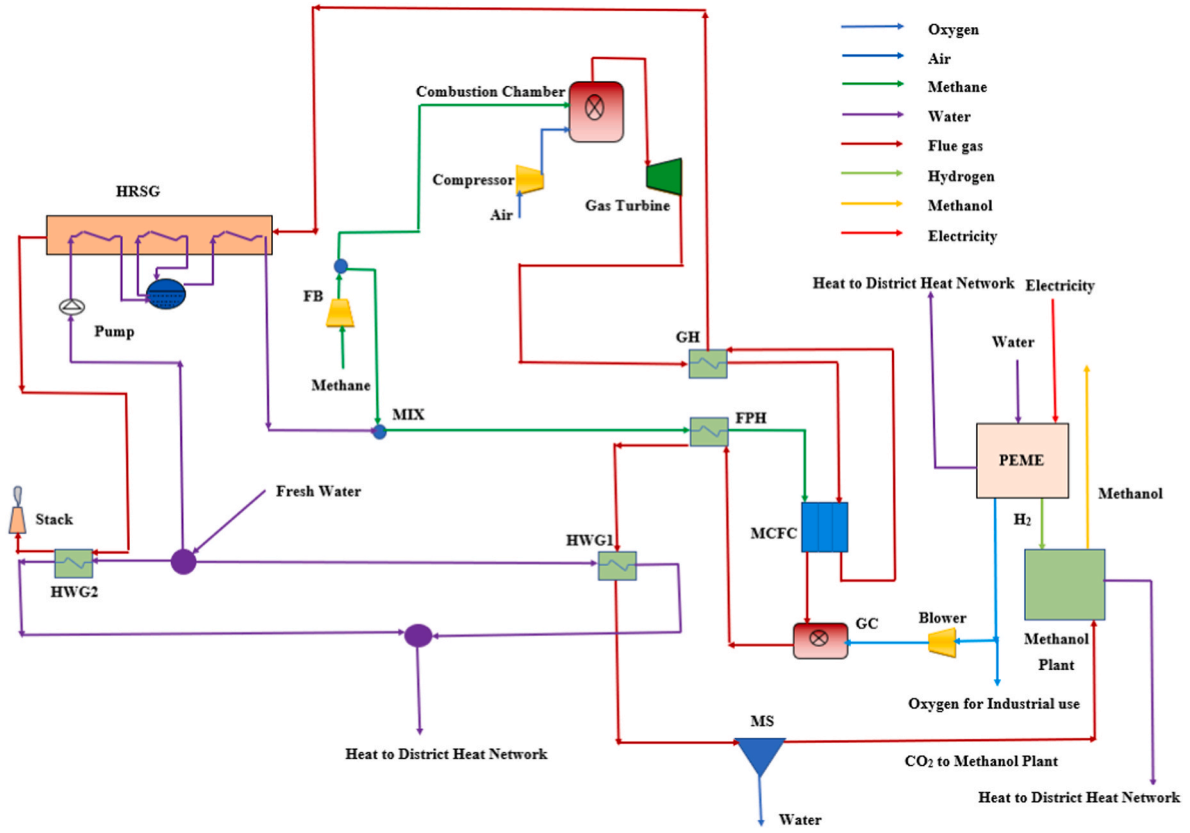

Fig. 6. Schematic representation of GT-MCFC-Methanol system.

The conceptualized plant performance is summarised in Table 2.

4. Case study 1: GT-MCFC plant

For the first case study the main power generation block has been changed. Instead of a SOFC unit, a conventional gas turbine (GT) plant is taken for the power generation at the upstream position. The GT exhaust goes to the cathode side of MCFC stack. The MCFC cathode exhaust preheats the exhaust gas from the GT unit at the gas preheater (GH). Rest of the plant configuration remains the same as the main proposed plant as stated earlier. The schematic representation of the proposed plant for the case study-1 is depicted in Fig. 6. The operating condition (compressor pressure ratio, maximum turbine inlet temperature, compressor, and turbine efficiencies etc.) for the GT unit is taken from the previously published literature. To replicate the GT plant, an industrial commercial scale GT cycle has been referred here. An open-type GT cycle has been proposed to be integrated [47]. The fresh air is compressed with a compression ratio of 14 [48] into the combustion chamber where it burns the methane fuel. The air fuel ratio is used such a way so that the outlet temperature of the combustion chamber would be 1200 °C [48]. The high pressure and temperature after-combustion gas expands in the gas turbine up to the normal atmospheric pressure before entering the cathode side of MCFC. The outlet temperature at the turbine exhaust is slightly lower than the MCFC operating temperature (650 °C) considered here in this study. So, before going to the MCFC the GT exhaust is again heated by the MCFC cathode exhaust gas. After pre-heating the GT exhaust still there are quite handsome amount of heat is available in the MCFC cathode exhaust stream that is coming out from the gas pre-heater. Before going into the atmosphere, the residual waste heat, available in the cathode exhaust stream, is recovered via hot water generation which is proposed to supply into the district heat network as well. The arrangements for the post processing of the MCFC anode exhaust gas and its waste heat utilization followed by the moisture separation to produce pure CO_2 remain similar like the earlier plant configuration (Fig. 2). At the same time the PEM electrolyser and the methanol production plant configurations as well as their integration with the main power generation unit remain the same as the earlier plant (Fig. 2). All other important operating parameters like compressor and turbine isentropic efficiencies, mechanical efficiencies, generator mechanical and electrical efficiencies, combustion chamber efficiency etc. are considered in line with the values mentioned in earlier literature [47,48].

4.1. Performance analysis

The first law and second law analyses have been performed to evaluate the thermodynamic performance of the proposed system for the case study −1. Following the same methodology as stated in section 3.5, the input and output energy balance and mass balance have been carried out in detail. The first law efficiency of the proposed system for the case study-1 is estimated as follows

$$\eta_{first\ law} = \frac{En_{out}}{En_{total}} \tag{18}$$

where En_{total} represents the total energy input, En_{out} represents the total useful energy output from the system which is the sum of net work output, heat supplied to the district heat network and energy associated with the methanol.

For the second law analysis, second law efficiency has been estimated for the system for case study - 1. The second law efficiency of the proposed system is estimated by the following equation

$$\eta_{second\ law} = \frac{Exergy_{out}}{(Inlet\ Exergy)_{total}} \tag{19}$$

Here the input exergy are the sum of the fuel input exergy and the electrical work input at the PEM electrolyser. The output exergy

Table 3
Thermodynamic Performance of the Plant for case study −1.

Parameter	Numerical Value	Units
Fuel Input	0.014	kg/s
Electricity Input	1000	kW
Net power Output	240.5	kW
Net Heat supply to district Heat network	854.55	kW
Methanol Produced	0.024	kg/s
Oxygen Produced	0.0361	kg/s
First Law Efficiency	86.42	%
Second Law Efficiency	55.29	%

($Exergy_{out}$) of the system is comprised of the net work output from the system, the exergy value of the heat supplied to the district heat network, the total exergy (both physical and chemical) associate with the produced methanol and oxygen. The detailed calculation of the individual exergy outflow is already explained in section 3.5, not repeated here.

The plant performance output summary for the case study – 1 is summarised in Table 3.

The detailed inflow and outflow and an overall exergy balance of the plant for the case study – 1 is portrayed in Fig. 7.

5. Case study 2: GT-MEA plant

Likewise, the first case study for the second case study the main power generation block has been changed too. Instead of the SOFC unit, a conventional gas turbine (GT) plant is taken for the power generation at the upstream position. Along with the GT unit at the downstream instead of the MCFC unit a conventional monoethanolamine (MEA) based chemical absorption CO_2 capture unit is proposed to be integrated. As described earlier in section 4 the configuration and the design and operating parameters of the GT unit remains same as considered for the case study −1. The GT exhaust goes to the MEA capture unit. The GT exhaust temperature is substantially high to be send into the MEA capture unit. The GT exhaust is to be cooled up to the near atmospheric temperature before sending it into the absorber column of the MEA unit [49]. This gives a good opportunity to recover heat via hot water generation that is going to be supplied in the local district heat network. Then the flue gas is sent to the absorber column of the MEA system with the help of a gas blower [50]. Then the MEA plant is designed and modelled using the designed and operating parameter as in line with the previously published literature [51,52]. The separated and captured CO_2 is then compressed and send to the methanol production plant for CO_2 hydrogenation process. The configuration and design & operating conditions for the methanol plant and PEM electrolyser unit remain the same as stated earlier in detail. Rest of the plant configuration remains the same as the main proposed plant as stated earlier in section 2. The schematic representation of the proposed plant for the case study-2 is depicted in Fig. 8. Unlike the two previously proposed system configuration there is no need for pure oxygen for the post combustion process at the downstream of MCFC unit. So, the system proposed for the case study −2 produces comparatively more oxygen than the earlier two proposed configurations, that are going to be supplied for the industrial use. In all the previous literature it has been reported that the reboiler heat duty for the MEA capture unit can vary 3.7–4.4 MJ/kg of CO_2 [49–52]. Here in this study the reboiler heat dusty is taken as 4 MJ/kg of CO_2 [50] and it has been assumed that high quality waste heat, available in the whole integrated system, has been supplied to meet this reboiler heat duty. As a result, the overall net heat that are going to be suppled in the local district heat network is reduced in comparison to the other two earlier proposed systems. On the other hand, the auxiliary power consumption to operate only the MEA plant excluding the CO_2 compression

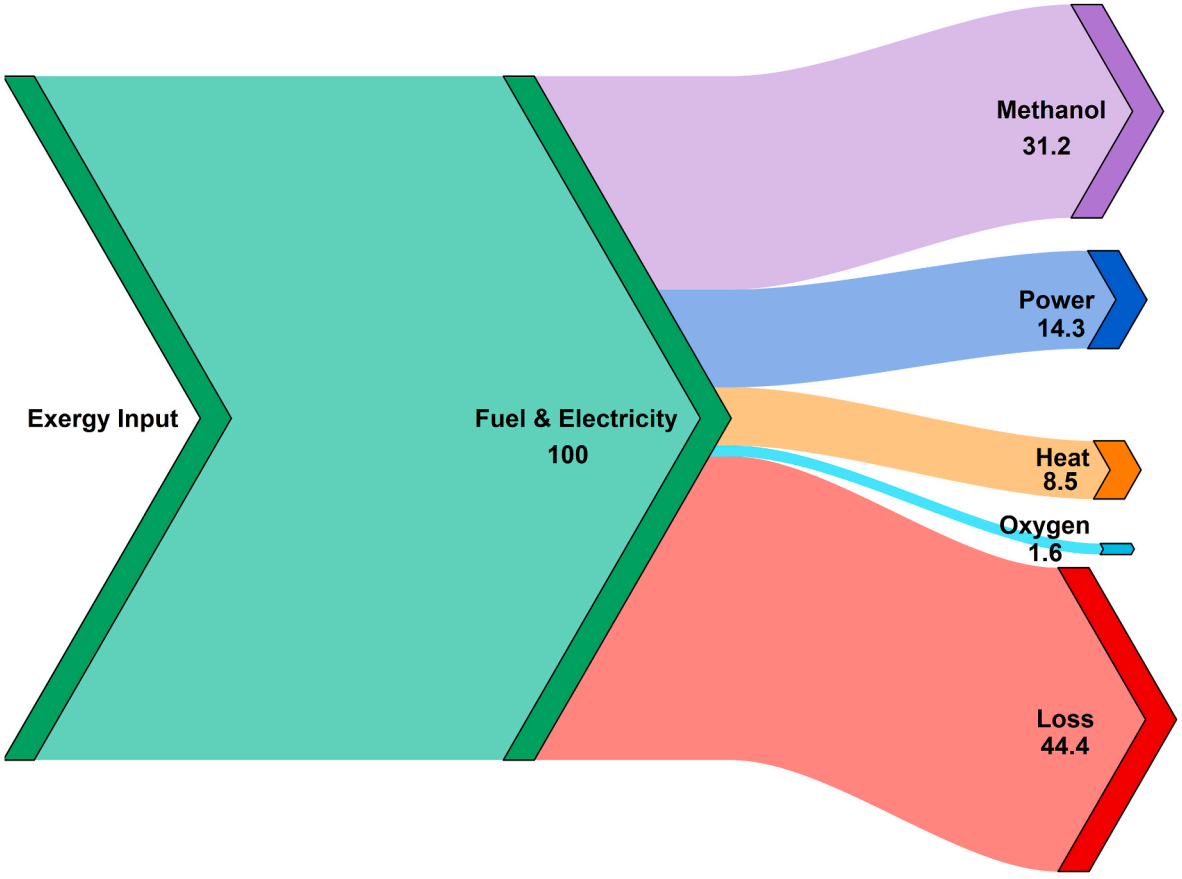

Fig. 7. Exergy flow of the GT-MCFC-Methanol system.

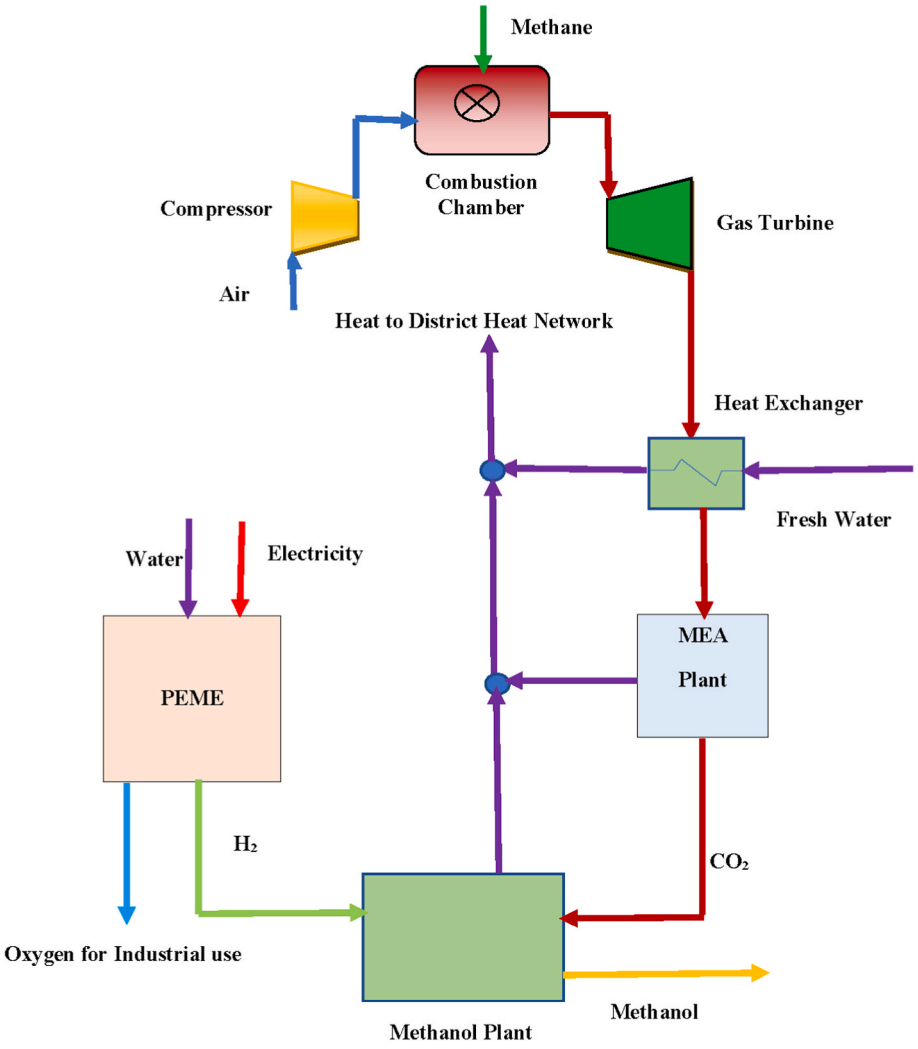

Fig. 8. Schematic representation of GT-MEA-Methanol system.

unit are taken as 4.757 kW/kg/s CO_2 [50]. This auxiliary power has been supplied from the power produced at the GT unit, resulting a lower net power output from the overall plant.

5.1. Performance analysis

Again, the first law and second law analyses have been performed to evaluate the thermodynamic performance of the proposed system for the case study −2.

Following the same methodology, the input and output energy balance and mass balance have been carried out as stated earlier in detail in section 3.5.

The first law efficiency of the proposed system for the case study-2 is estimated as follows

$$\eta_{first\ law} = \frac{Energy_{out}}{Energy_{in}} \tag{20}$$

where $Energy_{in}$ represents the total energy input into the system, $Energy_{out}$ represents the total useful energy output from the system which is the sum of net work output, heat supplied to the district heat network and energy associated with the methanol. The energy input comprised of the fuel energy input and the renewable electrical energy input. However, the detailed calculation for the energy out flow from the system is already explained in section 3.5, not repeated here. For the second law analysis, second law efficiency has been estimated for the system for case study - 2. The second law efficiency of the proposed system is estimated by the following equation

$$\eta_{\text{sec }ond\ law} = \frac{Net\ output\ Exergy}{Input\ Exergy} \tag{21}$$

Here, the input exergy is the sum of the fuel input exergy and the electrical work input (itself an exergy) at the PEM electrolyser. The net output exergy of the system is comprised of the net work output from the system, the exergy value of the heat supplied to the district heat network, and the total exergy (both physical and chemical) associated with the produced methanol and oxygen. The detailed calculation of the individual exergy outflow is already explained in section 3.5, not repeated here. The plant performance output summary for the case study – 1 is summarised in Table 4.

Table 4
Thermodynamic Performance of the Plant for case study −2.

Parameter	Numerical Value	Units
Fuel Input	0.012	kg/s
Electricity Input	1000	kW
Net power Output	215.8	kW
Net Heat supply to district Heat network	619.4	kW
Methanol Produced	0.024	kg/s
Oxygen produced	0.0361	kg/s
First Law Efficiency	75.58	%
Second law Efficiency	54.8	%

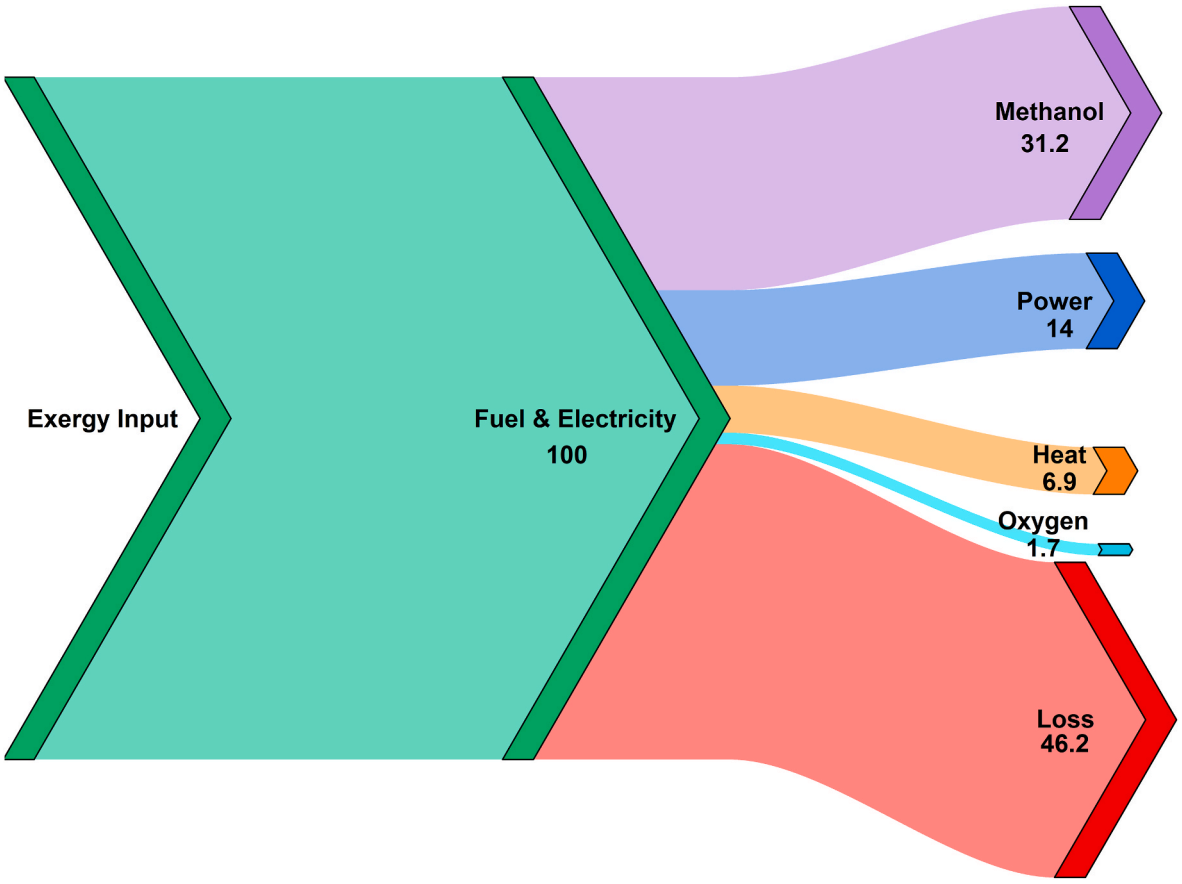

Fig. 9. Exergy flow of the GT-MEA-Methanol system.

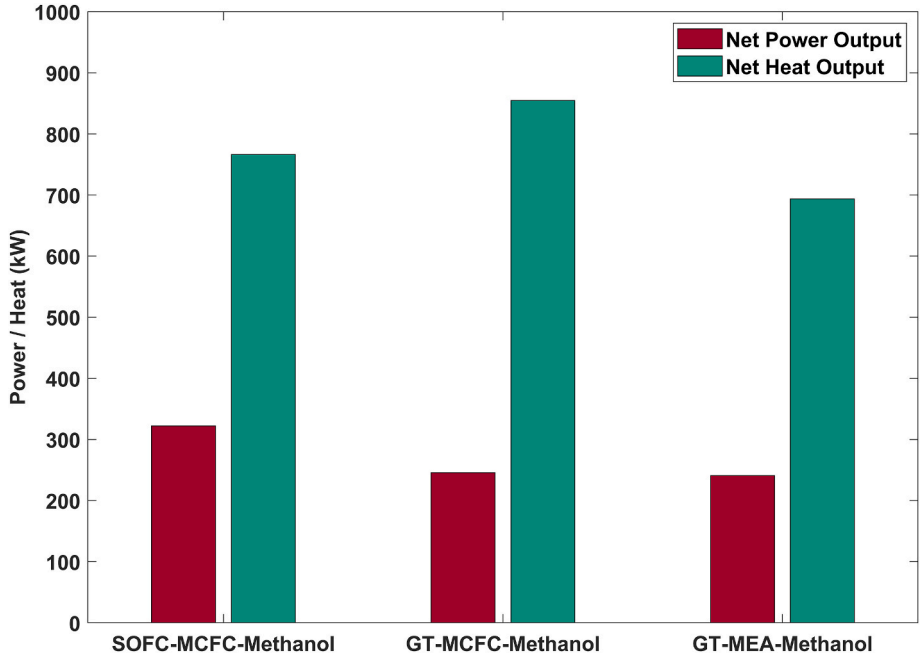

Fig. 10. Net power and net heat from the investigated systems.

The detailed inflow and outflow and an overall exergy balance of the plant for the case study – 2 is portrayed in Fig. 9.

6. Technical performance evaluation

6.1. Net power output and net heat supply to district heat network

Fig. 10 compares the net power output and available net heat from the investigated three system configurations. It is observed that the "SOFC-MCFC-Methanol system" generates the maximum amount of net power output, followed by the "GT-MCFC-Methanol system" and the "GT-MEA-Methanol system". In the SOFC-MCFC-Methanol system, SOFC generates 339.29 kW, MCFC produces 24.06 kW, and 41.01 kW of power is used in running auxiliary equipment. In the GT-MCFC-Methanol system, GT generates 211.6 kW, MCFC generates 58.26 kW, and ancillary equipment consumes 24.28 kW. GT is the single power producing unit in the GT-MEA-Methanol system, producing 266.78 kW, with the remaining 25.97 kW utilized to drive ancillary equipment. However, Fig. 10 also shows that the "GT-MCFC-Methanol system" yields the highest net heat output, followed by the "SOFC-MCFC-Methanol system" and the "GT-MEA-Methanol system". The methanol plant generates the same amount of heat for all the systems, which was 105.78 kW. Unlike the MCFC integrated systems, the "GT-MEA-Methanol system" required heat input for the MEA unit, which was 136 kW. The CO_2 in the gas turbine exhaust steam was more than the SOFC unit. Hence, the required fuel input for the MCFC to separate the amount of CO_2 from the gas turbine system was higher, which resulted in a greater power and heat output from the MCFC unit coupled to the gas turbine as compared to the one coupled with the SOFC system. As a result, the power output from the "SOFC-MCFC-Methanol system" is the highest one followed by the "GT-MCFC-Methanol system" and the "GT-MEA-Methanol system".

6.2. Exergy and exergy efficiency of the system

Fig. 11 compares the energy and exergy efficiencies of the three proposed configurations. It shows that the "GT-MCFC-Methanol system" yields the highest energy efficiency (86.72%), followed by the "SOFC-MCFC-Methanol system" (86.02%) and the "GT-MEA-Methanol system" (76.97%). As can be seen from the preceding subsection, the "GT-MCFC-Methanol system" has the most available heat for the district heat network. As a result, the GT-MCFC-Methanol system has the highest energy efficiency. However, the "SOFC-MCFC-Methanol system" yielded the maximum exergy efficiency (59.12%), followed by "GT-MCFC-Methanol system" (55.58%) and the "GT-MEA-Methanol system" (53.79%). In comparison to the other systems, the "SOFC-MCFC-Methanol" system produces the highest power, as shown in the preceding subsection. As a result, the SOFC-MCFC-Methanol system has the highest exergy efficiency.

6.3. Oxygen and methanol production for industrial use

The oxygen generated by the PEM electrolyser component is an essential system product that will be marketed for industrial usage. 0.036 kg/s of oxygen was produced by the 1 MW PEME system. In the "SOFC-MCFC-Methanol system" and the "GT-MCFC-Methanol system", some amount of oxygen is used for the combustion of MCFC anode

Table 5
Capital costs of different equipment and other important data for economic analysis.

Description	Capital cost	Ref
PEM Electrolyser	400 £/kW	[36]
Solid Oxide Fuel Cell	900 $/kW	[53]
Molten Carbonate Fuel Cell	3000 $/kW	[54]
Pump + Compressor + Heat Exchanger + Pipe works	202.5 $/kW	[55]
Hot Water Storage Tanks	20 $/kW	[56]
Heat Network	624 £/MWh	[57]
Gas Turbine	713 $/kW	[58]
e-Methanol Plant	1620 $/t	[59]
MEA based CO2 capture	1691 $/t	[60]
Renewable electricity price for PEM electrolyser	35.26 £/MWh	[36]
Lithium-ion battery	350 $/kWh	[61]
Electricity selling cost	0.1514 £/kWh	[62]
Methane cost	1.35 $/kg	[63]
Oxygen selling cost	17.75 £ for 300 L cylinder	[64]
Methanol selling cost	3.31 £/kg	[65]

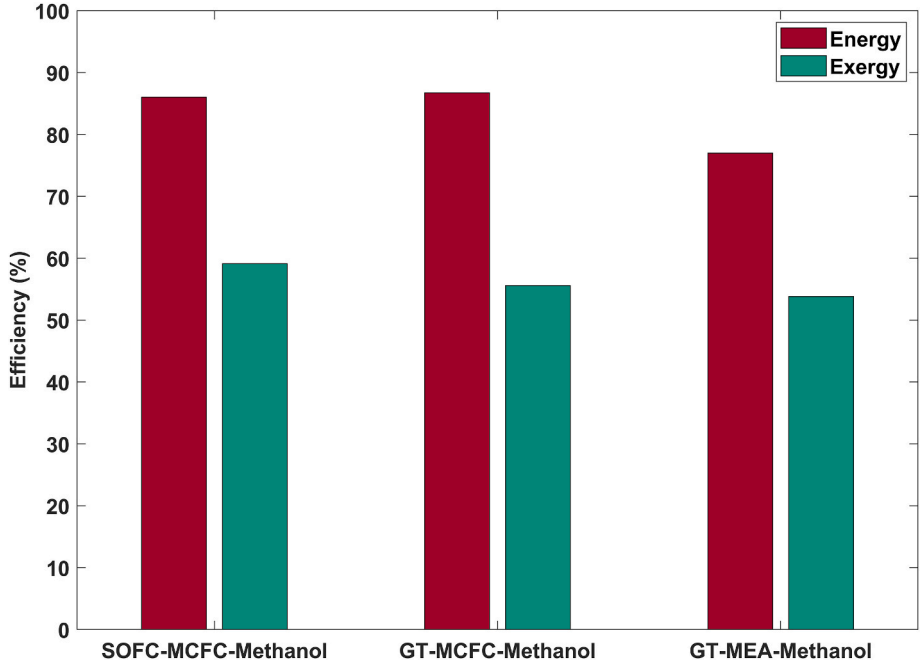

Fig. 11. Energy efficiency and exergy efficiency of the investigated systems.

exhaust gas at the downstream of MCFC unit. The GT-MEA-Methanol system, on the other hand, does not require any oxygen, hence the entire amount of oxygen is sold from this pant. So, both the "SOFC-MCFC-Methanol" and "GT-MCFC-Methanol system" produce 0.036139 kg/s pure oxygen for industrial use. Whereas the "GT-MEA-Methanol system" produces 0.038139 kg/s pure oxygen. All three systems are designed to capture and separate the same quantity of CO_2 coming out of the power generation unit. The CO_2 was utilized to make methanol using hydrogen from the PEM electrolyser in the methanol plant. Hence, same amount of methanol was generated from all three systems, which was 0.02399 kg/s.

7. Economic analysis

Table 5 contains the capital costs of various equipment as well as other key data for economic analysis.

The total capital cost (CAPEX) is the summation of all the components of the system, and it is estimated as follows:

$$CAPEX = \sum_i CAP_i \tag{22}$$

where, CAP_i is the capital cost of ith component.

The discount rate is considered to be 3% [36], and its lifespan is 30 years. The cost of yearly operation and maintenance is anticipated to be 2.5% of CAPEX [66]. The system needs periodic replacements of SOFC, MCFC and other components. The annual replacement costs have been projected to be 5% of CAPEX [66].

The total annual cost of the system is the combination of the annual capital cost, annual operational and maintenance cost, annual replacement cost, and annual fuel cost, as shown in the following equation.

$$COST_{Annual} = CAPEX_{Annual} + OPEX_{Annual} + REP_{Annual} + FUEL_{Annual} \tag{23}$$

7.1. Levelized cost of energy (LCOE)

The levelized cost of energy (LCOE) of the system can be determined by the following equation.

$$LCOE = \frac{COST_{Annual}}{Total\ Energy\ Production} \tag{24}$$

where unit of $COST_{Annual}$is $ and unit of '*Total Energy Production*' is kWh.

The levelized cost of energy (LCOEs) of the analysed systems are compared in Fig. 12 for two scenarios: "without battery storage" and "with battery storage". For "without battery storage" and "with battery storage" scenarios, the LCOE of the first system (SOFC-MCFC-Methanol system) is 0.06012 £/kWh and 0.0644 £/kWh, respectively. In comparison to the other analysed systems, the LCOE of the second system (GT-MCFC-Methanol system) is lower for both scenarios. The LCOE of "GT-MCFC-Methanol" system is predicted to be 0.0590 £/kWh without battery storage and 0.0622 £/kWh with battery storage. For both scenarios with and without battery storage, the GT-MEA-Methanol system has the highest LCOE among all of the systems. The LCOE of "GT-MEA-Methanol" system is 0.0782 £/kWh without battery storage and 0.0817 £/kWh with battery storage, respectively.

7.2. Payback period

Fig. 13(a)and (b) show a simple payback model for the proposed SOFC-MCFC-Methanol system in two different scenarios: "with battery storage" and "without battery storage," respectively. The payback period of the SOFC-MCFC-Methanol system is estimated to be 2.16 years without battery storage and 2.75 years with battery storage, respectively.

The simple payback periods of the other configurations have also been calculated and compared which is shown in Fig. 14. The "GT-MEA-Methanol" system has the largest payback period for both the scenarios with and without battery storage. The payback period for the GT-MEA-Methanol system is expected to be 5.57 years without battery storage and 4.86 years with battery storage, respectively.

8. Comparative performance analysis with other systems

In this section, the techno-economic performances of different systems integrated with SOFC or MCFC have been compared in a tabulated form. The proposed multigeneration system has energy and exergy

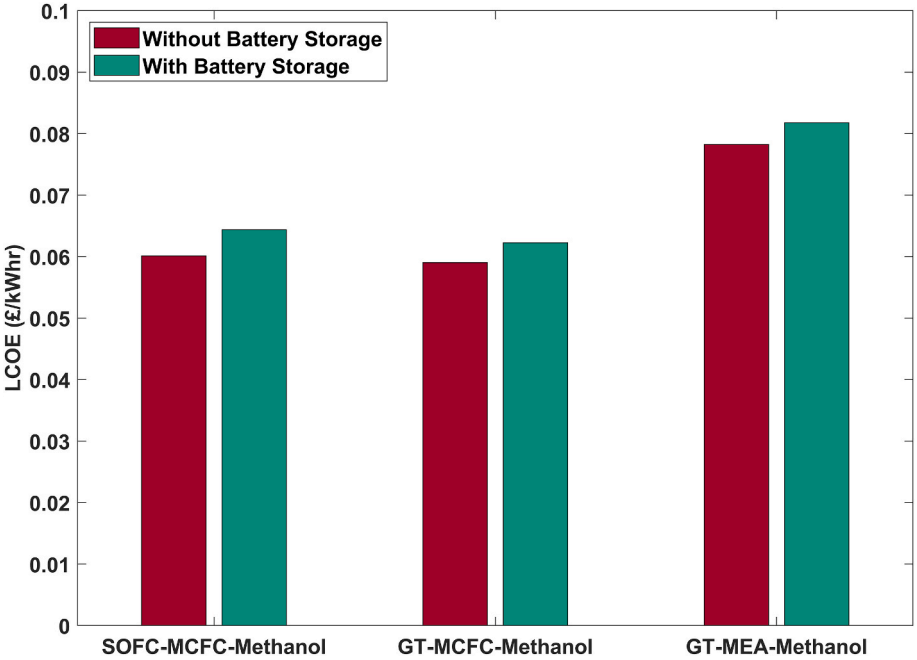

Fig. 12. Levelized cost of energy of the investigated systems.

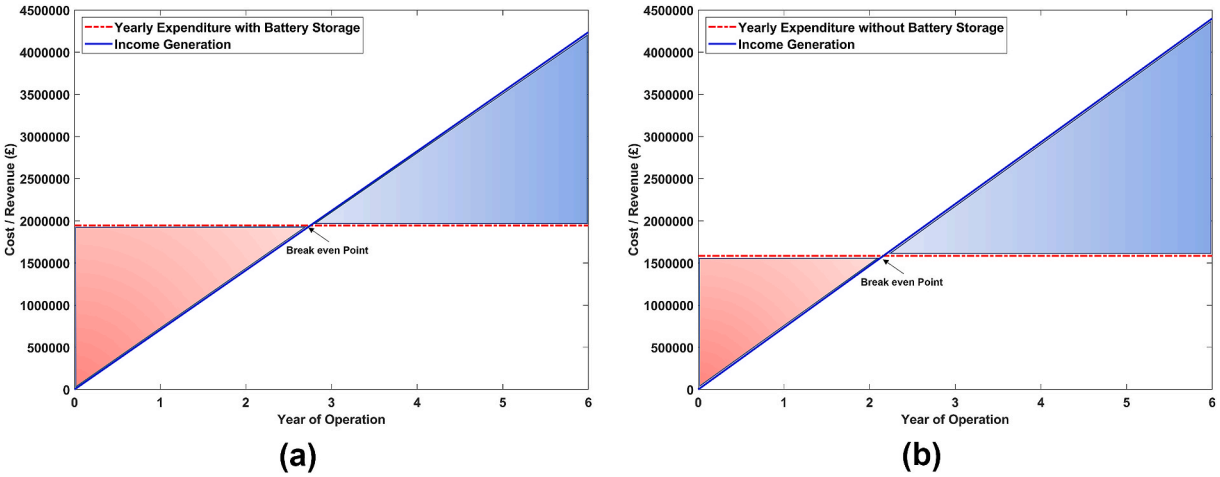

Fig. 13. (a) Simple payback model for the SOFC-MCFC-Methanol system with battery storage. (b): Simple payback model for the SOFC-MCFC-Methanol system without battery storage.

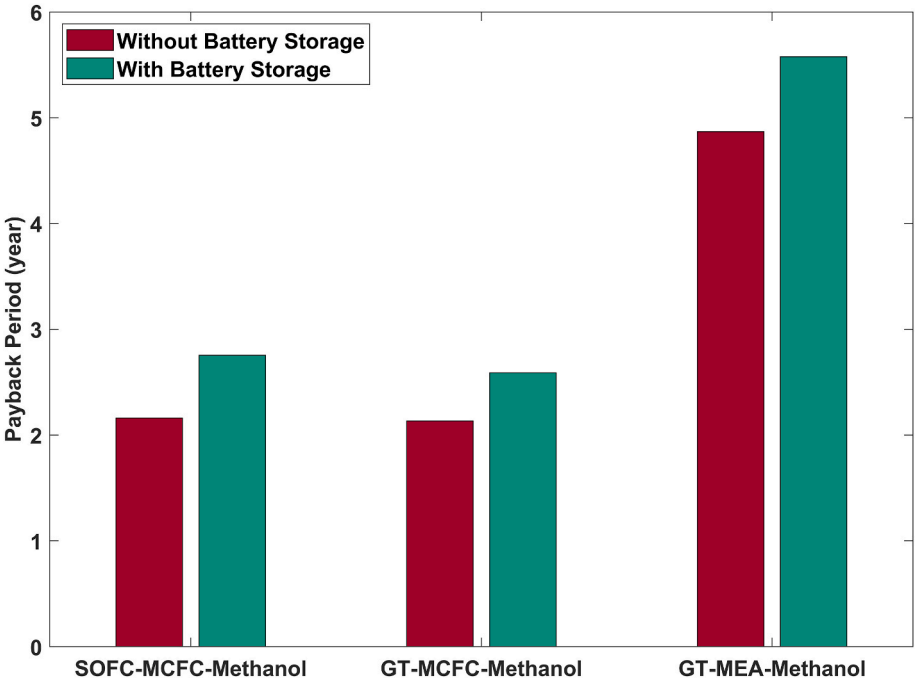

Fig. 14. Payback period of the investigated systems.

efficiency of 86.03% and 59.13%, respectively. The table shows that the proposed multigeneration system has much better thermodynamic performance than other systems. Furthermore, the LCOE of the proposed current multigeneration energy hub is 0.06 £/kWh, which is lower than many systems listed in Table 6.

9. Conclusions

Till the 100% transformation into renewable energy generation, carbon capture and utilization will be crucial in reaching the goal of reducing carbon emissions and achieving net zero emissions, especially in the transportation and mobility sectors. An integrated heat and energy system has been proposed in this study for an energy hub based on production and storage of power, heat, hydrogen, and oxygen. The hub consists of an electrolyser (PEM electrolyser), fuel cells (SOFC and MCFC) and a methanol generating plant. The PEM electrolyser produced H_2, O_2 and heat utilizing renewable electricity. Methane was employed as fuel in a solid oxide fuel cell (SOFC) to generate electrical power and heat. A molten carbonate fuel cell (MCFC) was used to separate CO_2 from the SOFC exhaust and to generate power, heat simultaneously as well. Thereafter, the segregated CO_2 was reacted with the H_2 from the electrolyser to produce methanol and heat. The heat from the electrolyser, fuel cells, and methanol production facility has been proposed to be fed into a district heating network at 75 °C. To assess the hub's techno-economic potential, energy, exergy, and economic assessments have been conducted. The following are the main observations concerning the proposed hub:

- The net electrical power and heat output from the hub was 321.95 kW and 766.4 kW, respectively.
- The plant also produced 0.024 kg/s of methanol and 0.036 kg/s of net oxygen.

Table 6
Techno-economic performances of different systems.

System configuration	Products	Efficiency	Levelized cost of electricity/ energy	Ref.
SOFC -GT hybrid system integrated with coal gasification	Power	41.6% (electrical)	82 $/MWh	[67]
SOFC-GT- steam cycle integrated with coal gasification	Power	44.6% (electrical)	77 $/MWh	[67]
Natural gas fired combined cycle with MCFC based CO_2 capture	Power	57.53% (electrical)	58.80 $/MWh	[68]
Multigeneration system integrating MCFC-thermally regenerative electro-chemical cycle, thermophotovoltaic cell, alkaline electrolyzer and absorption refrigerator	Power, Heating, Cooling and Hydrogen	86.8% (energy) 80.4% (exergy)	–	[69]
Biomass gasification based SOFC- GT and ORC integrated system	Power	49.29% (electrical)	65.4 $/MWh	[70]
CCHP system integrating SOFC, GT, ORC, and double effect absorption refrigeration cycle	Power, Heating and Cooling	63.21% (electrical); 62.67% (exergy)	–	[71]
Methane fueled SOFC-MCFC-GT and compressed air energy storage (CAES) integrated hybrid system	Power	60% (electrical)	–	[72]
Supercritical coal power plant in India retrofitted with calcium looping based CO_2 capture system	Power	–	93.7–119.9 €/MWh	[73]
CCHP system integrating MCFC, GT Stirling engine, Absorption Chiller	Power, Process heat and cooling	71.71% (energy)	–	[74]
CCHP system integrating solar aided MCFC, Steam turbine	Power, Heating and Cooling	65.89% (energy) 63.77% (exergy)	–	[75]
CCHP system diesel-fueled chemical looping hydrogen generation, SOFC, GT and absorption chiller	Power, Heating and Cooling	54.1% (electrical) 52.3% (exergy)	–	[76]

- The exergy efficiency of the proposed system was 59.12%. The levelized cost of energy (LCOE) for the proposed system was 0.06012 £/kWh.

Two case studies have been conducted to validate the proposed system's potential in contrast to existing systems. In the first case study, the SOFC was replaced with a conventional gas turbine, but everything else remained the same. The MCFC was replaced in the second case study by a typical MEA plant to extract CO_2 from the exhaust of a gas turbine. The key findings from the two case studies are summarised here:

- The exergy efficiencies were found to be 55.58% and 53.57% for the "GT-MCFC-Methanol" and "GT-MEA-Methanol" system, respectively.
- The comparison shows that the performance of the proposed system outperformed that of traditional gas turbine-based systems.
- The LCOE for the first case study ("GT-MCFC-Methanol" system) was 0.0590 £/kWh, whereas the LCOE for the second case study ("GT-MEA-Methanol" system) was 0.0782 £/kWh. As evident from the economic comparison, the proposed system's LOCE was similar to the first case study's and exceeded the second case study's LCOE.

Despite having the favourable results to go forward with decarbonising the transport sector and the district heat network, the main obstacle is the commercialization of low cost SOFC and MCFC technology. Additionally, there is uncertainty regarding the energy demand for both transportation and district heat, as well as the input side of renewable green hydrogen production. Balancing both supply and demand will be a significant challenge. This presents an opportunity for further research to conduct a comprehensive analysis of the system, utilizing practical energy demand data for specific energy hubs, communities, county councils, regions, or zones. The fuel cell-based system is a reliable energy generation device, but it may have limitations in meeting variable energy demand over a daily, monthly, or yearly period. It is probable that additional research will be necessary to develop an operational strategy for the proposed system to adapt to fluctuating demand.

Credit author statement

Samiran Samanta: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft. **Dibyendu Roy:** Conceptualization, Methodology, Software, Investigation, Writing - Original Draft. **Sumit Roy**: Conceptualization, Software, Supervision, Writing-Reviewing and Editing. **Andrew Smallbone**: Supervision, Project administration, Resources, Writing- Reviewing and Editing. **Anthony Paul Roskilly**: Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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