CONCEPTUAL DEVELOPMENT AND ANALYSIS OF SUSTAINABLE POWERING OPTIONS FOR HYBRID VEHICLES

by

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ABSTRACT

Hydrogen and ammonia are the carbon-free fuels that have the potential to replace the fossil fuels in the near future. In addition, they can also act as energy carriers and storage media for many applications; particularly in the transportation sector, which contributes around 25% of the global greenhouse gas (GHG) emissions, and a substantial reduction to this share will undoubtedly achieve better environmental conditions. In this thesis, six novel integrated systems for powering vehicles are conceptually developed and introduced. Five of the sixth systems that are proposed utilize clean energy carriers such as; ammonia and hydrogen. The sixth system exploits low GHG emission fuel represented in compressed natural gas. Solar energy is also harnessed and used via the utilization of the Photovoltaic (PV) panels to provide clean source of energy for two of the introduced powering systems. The introduced integrated systems were conceptually developed to for better efficiency and less environmental impact compared to the conventional vehicle systems that are using gasoline internal combustion engines (ICE). The systems in this thesis are primarily powered using very high energy density batteries such as lithium ion (Li-ion), fuel cells, photovoltaic panels, gas turbine that utilizes natural gas as a fuel, and internal combustion engines (ICE) that burn only carbon-free fuels.

All the system are thermodynamically modeled by applying energetic and exergetic approaches via the Engineering Equation Solver software (EES). Detailed electrochemical models for the proton exchange membrane fuel cell (PEMFC) and ammonia electrolyte cell (AEC) are also developed. The obtained results are validated by using energy and exergy analyses and available data from the literature. Moreover, exergoeconomic analysis has been carried out for the proposed systems. The Genetic Algorithm is utilized to optimize the introduced systems to achieve the optimum performance with the least possible cost for each system. For the same power output of 118 kW, the overall energy and exergy efficiencies of system 1, which comprises Li-ion battery, PEMFC system and PV panels are found to be 45.9% and 46.4% at a fuel cell current density of 1150 mA/cm² respectively. The energy and exergy efficiencies of system 2, which comprises Li-ion battery, PEMFC system, PV panels and AEC unit are found to be 47.5% and 47.4% at a fuel cell current density of 1150 mA/cm² respectively. The overall energy efficiencies of systems 3, which comprises ammonia-hydrogen ICE and ammonia dissociation separation unit (ADSU) and system 4, which comprises ammonia-hydrogen ICE, ADSU and PEMFC system are obtained as
31% and 38.6% respectively. The overall exergy efficiencies of systems 3 and 4 are found to be 28.8% and 36.2% respectively. The overall energy and exergy efficiencies of system 5, which consists of ammonia-hydrogen ICE, thermoelectric generators (TEG) and AEC unit are found to be 31.1% and 28.9% respectively. The overall energy and exergy efficiency of system 6, which consists of Li-ion battery, gas turbine, TEG, organic Rankine cycle (ORC) and absorption chiller are found to be 32.3% and 29.2% respectively.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area, (m^2)</td>
</tr>
<tr>
<td>a</td>
<td>Membrane activity</td>
</tr>
<tr>
<td>c</td>
<td>Cost per unit exergy ($/kWh)</td>
</tr>
<tr>
<td>(C_d)</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>(\dot{C}_D)</td>
<td>Cost rate of exergy destruction ($/h)</td>
</tr>
<tr>
<td>(\dot{C})</td>
<td>Cost rate ($/h)</td>
</tr>
<tr>
<td>CC</td>
<td>Capital cost ($)</td>
</tr>
<tr>
<td>CRF</td>
<td>Capital recovery factor</td>
</tr>
<tr>
<td>Bp</td>
<td>Battery power, kW</td>
</tr>
<tr>
<td>(D_{eff})</td>
<td>Diffusion coefficient, (m^2/s)</td>
</tr>
<tr>
<td>E</td>
<td>Actual cell voltage, V</td>
</tr>
<tr>
<td>(E_{act})</td>
<td>Activation overpotential, V</td>
</tr>
<tr>
<td>(E_{ohm})</td>
<td>Ohmic overpotential, V</td>
</tr>
<tr>
<td>(E_{conc})</td>
<td>Concentration overpotential, V</td>
</tr>
<tr>
<td>(\dot{E}_x)</td>
<td>Exergy rate, kW</td>
</tr>
<tr>
<td>ex</td>
<td>Specific exergy, (kJ/kg)</td>
</tr>
<tr>
<td>f</td>
<td>Exergoeconomic factor</td>
</tr>
<tr>
<td>F</td>
<td>Faraday constant, (C/mol)</td>
</tr>
<tr>
<td>h</td>
<td>Specific enthalpy, (kJ/kg)</td>
</tr>
<tr>
<td>(h_c)</td>
<td>heat transfer coefficient, (W/m^2K)</td>
</tr>
<tr>
<td>i</td>
<td>Interest rate, %</td>
</tr>
<tr>
<td>I</td>
<td>Current, A</td>
</tr>
<tr>
<td>J</td>
<td>Current density, (A/m^2)</td>
</tr>
<tr>
<td>(J_L)</td>
<td>Limiting current density, (A/m^2)</td>
</tr>
<tr>
<td>(J_{oa})</td>
<td>Exchange current density of the anode, (A/m^2)</td>
</tr>
<tr>
<td>(J_{oc})</td>
<td>Exchange current density of the cathode, (A/m^2)</td>
</tr>
<tr>
<td>(J_0)</td>
<td>Exchange current density, (A/m^2)</td>
</tr>
<tr>
<td>K</td>
<td>Equilibrium constant</td>
</tr>
<tr>
<td>n</td>
<td>Number of years</td>
</tr>
<tr>
<td>(\dot{N})</td>
<td>Molar flow rate, (mol/s)</td>
</tr>
<tr>
<td>N</td>
<td>Number of moles</td>
</tr>
<tr>
<td>OM</td>
<td>Operational and maintenance, $</td>
</tr>
<tr>
<td>P</td>
<td>Pressure, bar</td>
</tr>
<tr>
<td>PEI</td>
<td>Electrolysis power, kW</td>
</tr>
<tr>
<td>(\dot{Q})</td>
<td>Heat rate, kW</td>
</tr>
<tr>
<td>R</td>
<td>Gas constant, (kJ/kmol K)</td>
</tr>
<tr>
<td>s</td>
<td>Specific entropy, (kJ/kg K)</td>
</tr>
<tr>
<td>(S_t)</td>
<td>Solar radiation, (W/m^2)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature, (^\circ C) or K</td>
</tr>
<tr>
<td>TCC</td>
<td>Total cost of the component. $</td>
</tr>
<tr>
<td>Tor</td>
<td>Torque, N.m</td>
</tr>
<tr>
<td>u</td>
<td>Speed, m/s</td>
</tr>
<tr>
<td>V</td>
<td>Voltage, V</td>
</tr>
</tbody>
</table>
Wind speed, m/s
Power, kW
Molar fraction

Greek Letters
\( \alpha \) Symmetry factor, Road gradient angle, deg
\( \beta \) Reduction ratio
\( \delta \) Element thickness, m
\( \eta \) Energy efficiency
\( \lambda_{\text{mem}} \) Membrane water content
\( \sigma_{\text{mem}} \) Membrane conductivity, 1/\( \Omega \) cm
\( \mu \) Rolling resistance coefficient
\( \rho \) Material resistivity, \( \Omega \) m
\( \varphi \) Road friction coefficient
\( \psi \) Exergy efficiency
\( \omega \) Engine speed

Subscripts
0 Ambient condition
1, 2, \ldots i State Points
an Anode
c a Cathode, cabin
Ch Chemical
cha Charging
Comp Compressor
c cool Cooling
cp Circulation pump
d Differential, decomposition
dis Displacement
dr Drag
e Electrolyte
ex Exhaust
f Fuel
F Frontal
H Hot
dis Discharge
Fc Fuel cell
Hex Heat exchanger
Ke Kinetic
m Maximum
MEP Mean effective pressure
n Semiconductor “n” type
p Semiconductor “p” type
Pe Potential
Ph Physical
Pr Pressure regulator
so Solar
sys System
Turb Turbine
v Volumetric

**Acronyms**

- AEC Ammonia electrolyte cell
- ADSU Ammonia dissociation separation unit
- BSEC Brake specific energy consumption
- CI Compression ignition
- DSU Dissociation separation unit
- EES Engineering equation solver
- EPA United States Environmental Protection Agency
- FTP Federal test procedure
- GHG Greenhouse gas
- He Heat exchanger
- HPU Hydrogen purification unit
- ICE Internal combustion engine
- nfc Number of fuel cell cells
- NT Nitrogen turbine
- NEDC New european driving cycle
- ORC Organic Rankine cycle
- PCU Power control unit
- Pr Pressure regulator
- SI Spark ignition
- TEG Thermoelectric generator
- THS Total hydrogen saved
- UNEC United Nations Economic Commission for Europe
- WLTP Worldwide harmonized light vehicle test procedure
CHAPTER 1: INTRODUCTION

1.1 Energy and Environmental Overview

As shown in Fig. 1.1, the transportation sector is responsible for around 29% of the worldwide total final energy consumption in 2015 [1]. In addition, United States Environmental Protection Agency (EPA), announced that the transportation sector was the second largest source of the greenhouse gas (GHG) emissions in the United States in 2015 as shown in Fig. 1.2 [2]. Environment Canada stated that the transportation sector in Canada was responsible for emitting 24% of the total national GHG emissions in 2015, see Fig. 1.2, the emissions released from passenger and freight travels shared around 96% of these emissions [3]. Moreover, vehicles are considered the primary cause of both the energy crisis and greenhouse gas emissions. For instance, they are responsible for 60.5% of the global petroleum consumption in the United States, and they are expected to increase the global CO$_2$ emissions by 30-50% by 2050 [4].

![World energy consumption breakdown by economic sector in 2015](data.png)

Fig. 1.1 World energy consumption breakdown by economic sector in 2015, data from [1].

1.2 Transportation Options

Transportation is one of the vital sectors that consumes a substantial share from the worldwide energy consumption and produces a significant amount of greenhouse gasses. Transportation options are varied nowadays and are including air transportation represented in passenger and commercial airplanes, water transportation via barge, boat,
ship or sailboat, rail transportation by trains and road transportation such as automobiles, buses, trucks, bicycles. The current study will be focusing on the passenger vehicles.

Fig. 1.2 Greenhouse gas emissions by sector in the United States and Canada in 2015, (A) the United States, (B) Canada, obtained from [2,3].

1.3 Powering Options for Vehicles

Powering vehicles can be achieved through numerous options as shown in Fig1.3. For instance, utilizing internal combustion engines (ICE) that are fueled by conventional fuels such as gasoline, diesel and natural gas. ICEs can also be fueled with renewable fuels such as biofuel, ethanol, and methanol. Fueling ICE with carbon-free fuels such as ammonia and hydrogen is also a possible and promising way to power the vehicles. Electric options represented in the Utilization of fuel cells is one of the encouraging options to power the vehicles, as well as, batteries. In the electric options, supercapacitors can be used to meet the peak power demand during vehicle operation. Solar energy, represented in the photovoltaic panels can be used to provide free electric power to the vehicle powering system, this obtained power can be used to charge the battery when needed.

1.3.1 Conventional Fuels

Fossil fuels are that kind of energy that exists due to the decomposition of the decaying living organisms that were buried millions of years ago. Time, pressure and heat played the vital role to change the organic matter to one of the three main types of fossil fuels, which are coal, natural gas, and oil. The following are the most common types of fossil fuels that can be used in vehicles:
- Petroleum such as Liquefied petroleum gas (LPG), Butane, Jet fuel, Fuel oil, Gasoline, Diesel fuel.
- Natural gas such as compressed natural gas (CNG), Liquefied natural gas (LNG).

![Diagram of Powering options](image)

Fig. 1.3 Different powering options for vehicles.

### 1.3.2 Renewable Fuels/Energy

Renewable fuel can be defined by the fuel that can be continuously replenished by nature. For instance, biofuels, or the fuel that can be produced from renewable processes such as producing hydrogen from renewable resources and nuclear energy. In addition, Renewable energy is the energy which results from resources that are naturally renewed on human timescales, such as wind, sunlight, tides, rain, waves, and geothermal heat. Renewable energy can act as an adequate substitute for the conventional fuels in many different areas such as ICE, electricity generation, air, and water heating/cooling. Biofuel is a liquid fuel composed of mono-alkyl esters of long chain fatty acids derived from animal fats and other non-edible oil sources, vegetable oils and compatible with the standard requirements of ASTM D6751 [5–7]. The available types of biofuels are renewable methanol, biogas, biobutanol, bioethanol, biodiesel, and biohydrogen. Biofuel is characterized by low emission, non-toxicity, and it is recognized as a safe and green source of energy [7]. The biofuels can be categorized into the first generation, which generally results from edible food crops and vegetable oils. Food crops include rice, potato wastes, barley wheat, etc. vegetable oils including soybean oil, sunflower oil, corn oil, palm oil, coconut oil mustard oil. Second generation (2G), which can be formed from different types of feedstock, ranging from lignocellulosic feedstock to municipal solid waste and animal fat, wood, non-food crops, waste cooking oil, and jatropha curcas. The cost of production and the sophisticated equipment needed for the production compared with 1G make the second generation not promising for commercial production. However, 2G biofuel can be used in
diesel engines without any alteration in the ignition setup of the engine and can work efficiently compared with gasoline ICE when gasoline is blended with 2G biofuels with a ratio ranging from 15 to 20%. Third Generation (3G) biofuels are fuels which can be generated from microalgal biomass [6,8,9]. Fourth Generation (4G) biofuels are defined in different ways in the literature. Azad et al. [6] defined it as fuels that can be generated by carbon captured from the environment by using advanced technologies like petroleum-hydro-processing. While Lu [10] defined biofuel production by utilizing a chemical process that can be used in the algae metabolic engineering forms to produce renewable 4G biofuel.

Solar energy is one of the most important renewable energy sources on earth. Solar energy generation involves the utilization of the sun's energy to afford hot water via solar thermal systems or electricity via solar photovoltaics, which are commonly used in vehicular applications. Photovoltaic cells are devices that convert sunlight or solar energy into direct current electricity. The main part a PV system is the PV cell, which is a semiconductor device that changes solar energy into direct current electricity [11,12].

1.3.3 Electric options
Fuel cell, batteries are two options that can be used to power any electric vehicles as they can supply electricity to the electric motor, which in turn will provide the traction to the vehicle. They are entirely environmentally friendly and clean possible options for powering electric vehicles. The fuel cell can be defined as an electrochemical energy conversion device that generates electricity directly from chemical energy, the by-products are only water and heat, which promotes it as an excellent source of clean energy. Fuel cells can provide much higher efficiency compared to conventional energy process. Fuel cells can be categorized according to electrolyte nature, their operating temperature, type of ions that can be transferred via the electrolyte, type of reactants that are used [13]. The common types of fuel cells can be listed as follows:

- Proton Exchange Membrane Fuel Cells (PEMFC).
- Direct Methanol Fuel Cells (DMFC).
- Alkaline Fuel Cells (AFC).
- Phosphoric Acid Fuel Cells (PAFC).
- Solid Oxide Fuel Cells (SOFC).
- Molten Carbonate Fuel Cells (MCFC).

An electric battery is a device comprising two or more electrochemical cells that have the ability to change the stored chemical energy into electrical energy, batteries are used in electric vehicles to supply the electric power to the electric motor and to store the excess electricity that can be recovered through any additional installed parts in the vehicles such as the dynamo. There are numerous types of batteries that can be utilized in the electric vehicles, and they can be itemized as follows [12]:

- Nickel based batteries.
- Sodium-based batteries.
- Lead acid batteries.
- Metal-air batteries.
- Lithium batteries.

Supercapacitors can assist batteries in powering electric vehicles. They are characterized by the rapid charging and discharging time, which can reach few seconds, and it can endure many charging and discharging cycles. Thus, they can be efficiently used to capture the electric energy recovered from the wasted kinetic energy during braking and supply it to the vehicle powering system during the transition phases such as acceleration where the electric power is required to be supplied in short time. This action can reduce both fuel utilization and harmful gases emissions during vehicle operation [14].

### 1.3.4 Pneumatic Options

This type of systems is designed to help in the downsizing and supercharging pattern, in such a way to reduce the fuel consumption and make it comparable to that of hybrid electric powertrains. The pneumatic system can reduce the weight of the vehicle and the associated costs of using the hybrid option. A fully variable charge valve is utilized to connect the cylinders of the ICE with a typical pressure tank. During the vehicle braking phases with no fuel supply, the engine will have the ability to accumulate the air and pump it into the pressurized air tank. The stored pressurized air can be utilized again during vehicle starting, or it can be used to drive the vehicle in the pneumatic motor mode, and as a result, it will mitigate the fuel consumption [15,16].
1.3.5 Carbon Free Fuels

Carbon-free fuels are clean fuels because they can be combusted in an environmentally benign way without releasing any harmful emissions such as GHG. These fuels can be utilized efficiently and in a competitive way compared to the conventional fuels with minor modifications in the ICE. Hydrogen, ammonia and nuclear fuel are the primary examples of such fuels. Hydrogen is a promising energy carrier and has all the potential to replace fossil fuels. Its combustion produces only heat and water without any harmful combustion gases. Beside combusting it, hydrogen can be utilized in fuel cells to produce electricity by reacting it electrochemically with oxygen. Further research development is required in the areas of hydrogen production, use and storage to permit the use of hydrogen as potential near future fuel that can perform efficiently in an environmental way and satisfy the sustainability measures. The high conversion efficiency of fuel cells, which can reach up to 60% and the high efficiency of electric motors, which can attain up to 90% promote the combination of fuel cells and electric motors as a highly efficient combination compared to ICEs efficiency [17]. In addition, hydrogen in its gaseous state can overcome the issues of using liquid fuels in combustion process of the ICE, such as cold wall quenching, vapor lock, poor mixing and inadequate vaporization [18]. Hydrogen, as a fuel, encounters some drawbacks that might affect considering it as a potential fuel. For instance, applying global hydrogen economy is not currently feasible, lack of hydrogen distribution infrastructure, having the adequate infrastructure will ensure the safety of using hydrogen since it’s volatile and has a low flash point. Hydrogen has a low volumetric energy density compared to gasoline. Therefore, a large volume is required to store hydrogen and even storing hydrogen in compressed gaseous state or in the compressed liquefied state is not entirely satisfactory and requires further improvement and research [19].

Ammonia has all the potential to replace hydrogen as a clean fuel for the following reasons. Cost per volume for storing hydrogen as an energy source is three times more costly compared to storing ammonia, ammonia distribution infrastructure is available with the ability to deliver it in large amounts, and storing ammonia is way easier than storing hydrogen since ammonia can be stored as a liquid at 20 °C and 8.7 bar. Moreover, it’s a convenient replacement of gasoline in vehicle applications because the energy content of ammonia is comparable to that of gasoline [19,20]. Utilizing ammonia as a clean source of
energy is convenient because it can be combusted in an environmentally way. It has high octane rate and consequently can perform efficiently in ICE, dissipate rapidly in the air due to its light density. In addition, any leakage can be quickly noticed by a nose in concentrations as low as 5 ppm [20].

1.4 Electric Vehicles
Developing the technology of electric vehicles will have a significant impact in reducing fuel consumption in the transportation sector leading to a reduction in the greenhouse gas (GHG) emissions. The recent technical development and improvements in electric vehicles design, advances in fuel cell technology, motors, controllers and rechargeable batteries promote the electric vehicle as a successful candidate to replace the conventional vehicles. The electric vehicle can be categorized as follows [12,21]:

- Battery electric vehicle (BEVs).
- Fuel cell vehicles (FCVs)
- Plug-in hybrid electric vehicles (PHEVs).
- Hybrid electric vehicle (HEVs).
- Hybrid hydraulic vehicles. (HYHVs).
- Pneumatic hybrid vehicles. (PHVs).
- Vehicles that store energy by alternative means such as flywheels or supercapacitors.
- Vehicles supplied by power lines.

1.5 Motivation and Novelties of the Study
Achieving sustainability in transportation area would reduce the negative environmental impact of the transportation sector represented in the greenhouse gas emissions. Also, it will reduce the dependence on fossil fuels. Therefore, the solution to achieve better sustainability is to use clean sources of fuel to power the vehicles and to develop efficient systems for vehicle propulsion. Many solutions are suggested by authors in the open literature. For instance, using solar energy, fuel cells, renewable fuels, batteries, etc. However, the research found in the literature were not focusing on using different integrated powering options to operate the vehicles. The majority of the powering solutions were with either one powering option such as using batteries or fuel cells or integrating
two powering options such as fuel cell and ICE, or integrating fuel cell and battery system. Current research introduces the idea of integrating triple powering options. For example, integrating fuel cells, batteries and PV, which will provide a realistic, sustainable solution and higher efficiencies for the vehicle operating system. Moreover, all the developed systems in this study are using carbon-free fuels such as hydrogen and ammonia to mitigate harmful emissions. However, only one system is developed to use natural gas as a fuel. Promoting natural gas as a replacement for gasoline is also one good option to protect the environment. Furthermore, all the proposed systems in the literature are barely analyzed using the second law of thermodynamics, which is a powerful tool that can provide an accurate evaluation for the performance of any energy system. Therefore, all the suggested systems are analyzed using exergy approach. All the systems are developed to achieve the highest possible recovery of any waste energy from the systems to increase its efficiency. In addition, the novel integrated systems are compared based on an economic overview to provide a comprehensive overview towards the most sustainable powering option. The novelties of this thesis can be listed as follows:

- Six novel systems are developed and analyzed using exergoeconomic analysis and energy and exergy approaches, systems are also optimized using genetic algorithm.
- To reduce hydrogen consumption and for better vehicle range, integration of PV panels with a fuel cell system is introduced.
- It is the first study to integrate PV panels with AEC to produce compressed hydrogen on board and extend the vehicle range; this system also has the potential to utilize the PV system during vehicle parking to produce compressed hydrogen that can be used later during vehicle movement.
- Hybridizing a fuel cell system with ICE, at which the fuel system operates only on hydrogen that is generated onboard from ammonia DSU, at which the exhaust gases released from ICE are used to run the DSU.
- Novel integration between TEG and AEC to produce hydrogen onboard to supply it to an ICE running on an ammonia-hydrogen blended fuel. The integration was successful in sustaining the required supply of hydrogen into the ICE guaranteeing an adequate ICE performance.
- Integrating gas turbine with TEG unit and organic Rankine cycle (ORC), at which the ORC will be used to cool down the TEG unit and consequently maximizing the electricity that can be recovered from gas turbine exhaust gases. The remaining energy in the released exhaust stream will be used to cool the vehicle cabin via the absorption chiller system.

- Exergy analysis is combined with dynamic analysis through simulating the exergy destruction rate of the different components along with the exergy recovered during the different phases of the driving cycle.

1.6 Objectives of the Study

The primary objective of this study is to propose and analyze six novel integrated energy systems for vehicular application. All the energy systems will be based on renewable energy sources and sustainable energy carriers, fuel cells, ammonia fueled internal combustion engines and gas turbine. In addition, the effect of using carbon-free fuels like hydrogen and ammonia will be examined. The developed systems will be compared with each other based on energy and exergy efficiencies to detect the most efficient system. An exergoeconomic analysis and optimization study will be applied to all systems. The detailed objectives of this study can be listed as follows:

- To conduct comprehensive thermodynamic modeling for the proposed integrated systems. All mass, energy, entropy, and exergy balance equations will be stated for each component of the proposed systems.

- To analyze each system energetically and exergetically:
  - Determine the flow energy and exergy for each stream in the system.
  - Identify exergy destruction rate and energy losses for each component.
  - Calculate energy and exergy efficiencies.

- To conduct exergoeconomic analysis for each system:
  - Cost determination for each line of the system.
  - Exergy destruction cost calculation of each component.
  - Estimate of the purchase cost of each component.

- To assess the systems through complete parametric studies:
• Identify the influence of changing environmental condition (such as environment temperature) on the performance evaluation of each system studied.

• Perform comprehensive parametric studies to investigate the effect of varying different design and operating parameters on the system performance.

- To perform an optimization study for each system to identify the optimal design parameters:
  • Define different objective functions for the system.
  • Define the constraints for each system.
  • Define the decision variables for each integrated system.

1.7 Thesis Outline

This thesis consists of six main chapters. In the first chapter, an introduction and background information regarding energy utilization and environmental impact of the transportation sector, transportation options, and vehicle powering options are provided. The importance of using fuel cells and carbon-free fuels such as ammonia and hydrogen are highlighted along with a classification of the available electric vehicles. Furthermore, the novelties of the proposed integrated systems along with the motivation and objectives of this thesis are included. Chapter 2 provides a comprehensive literature review on the different vehicle powering options including; ICE particularly the ones that are operating using carbon-free fuels such hydrogen and ammonia, fuel cell systems, the use of solar energy as a potential powering source. Moreover, a literature review of the different components that will be utilized in the proposed integrated systems such as ammonia electrolyte cell (AEC), thermoelectric generators (TEG) is incorporated. Chapter 3 shows and describes in details the proposed integrated systems and their components. Chapter 4 incorporates the general thermodynamic equations that are used to model the introduced integrated systems along with detailed thermodynamic modeling for the main components in each integrated system. An electrochemical model for both the fuel cell system and AEC unit is provided. Exergoeconomic analysis and total cost rate equations for the main parts of the system and optimization study are also presented in this chapter. Chapter 5 includes the obtained results for each integrated system along with a comprehensive comparison between all systems. The results of the exergoeconomic analysis and the optimization study
for each system are also provided. In chapter 6, conclusions are highlighted including the main findings from the thesis. Furthermore, the recommendations for further studies that might follow the presented work in this thesis are also included.
CHAPTER 2: LITERATURE REVIEW

In this chapter, the different powering option for passenger vehicles will be discussed, and the primary research reported in the area of vehicle propulsion will be highlighted. Moreover, state of the art of some components that will be used in the proposed integrated system is incorporated.

2.1 Internal Combustion Engines

The internal combustion engine can be fueled with a different type of Fuels. For instance, fossil fuels, biofuels, hydrogen, and ammonia. The proposed integrated systems are focusing on using carbon-free fuels such as ammonia and hydrogen. Therefore, the effect of using these carbon-free fuels on the ICE performance and emissions will be discussed in the following sections.

2.1.1 Hydrogen fueled ICE

Niemenen and Dincer [22] conducted a comparative exergy analysis for a gasoline and hydrogen-fueled ICEs. The results showed that, according to second law perspective, the hydrogen-fueled engine is efficient compared to the gasoline-fueled engine, as the exergy efficiency found to be 41.37% for the hydrogen ICE and 35.74% for the gasoline ICE. Mustafi et al. [23] performed an experimental work using a synthetic fuel consists of carbon monoxide and hydrogen in a variable compression ratio single-cylinder spark ignition (SI) engine. Experiments considered the variation of the air-fuel ratio to examine the effect of supplying rich and lean mixtures with changing speed, and they apply these conditions to two different compression ratios. The results showed that synthetic fuel generates about 30 and 20% lower engine power output compared to the gasoline-fueled engine and natural gas (NG) fueled engine respectively under similar operating conditions. Negligible hydrocarbons and CO emissions and higher CO$_2$ and NO$_x$ emissions are released using the synthetic fuel.

Chintala and Subramanian [24] studied the maximum useful work and irreversibility of a dual-fuel (hydrogen-diesel) diesel engine using exergy analysis. The results displayed that the maximum useful work of the diesel engine improved from 28% running on diesel only to 31.7% with dual fuel mode. In addition, total irreversibility of the engine reduced
considerably from 41.2% to 39.3%. Moreover, the energy efficiency of the H₂ fueled engine is observed to be augmented about 10% accompanied by 36% reduction in CO₂ emission. Das et al. [18] conducted an experimental comparative investigation of ICE running on CNG and hydrogen. The results showed that using hydrogen as a fuel was better than using CNG as a fuel due to the increase in the thermal brake efficiency and the reduction in the brake specific fuel consumption. In addition, the thermal brake efficiency was found to be 31.19% and 27.59% for hydrogen, and CNG fueled engines respectively.

Jafarmadar [25] carried out an energy and exergy analysis for dual fuel (diesel-hydrogen) Deutz engine at different gas fuel-air ratios. The results showed that by increasing the gas fuel-air ratio from 0.3 to 0.8, the cylinder peak pressure increases by 31.86%, and the in-cylinder peak temperature increases by 42.28%. The cumulative burned fuel exergy and exhaust exergy losses are also increased by 98.2% and 51.7 respectively. Nevertheless, the cumulative work exergy irreversibilities and exergy efficiency are reduced by 21.1%, 10.8%, and 9.2% respectively. Acikgoz et al. [26] performed a comparative energy and exergy analyses of hydrogen–methane blended fueled direct injection diesel engine. The results displayed that NOₓ emission of the hydrogen-fueled engine is about 7 times higher than CH₄ fueled engine. Hydrogen addition to the ICE is observed to decrease the engine HC and CO emissions. In addition, the brake specific fuel consumption showed a reduction and the thermal brake efficiency displayed an upsurge with increasing hydrogen fraction in the fuel blend. Iorio et al. [27] carried out an experimental work to investigate the effect of using methane, methane blended with hydrogen and compared it with gasoline in a small capacity direct injection SI engine. The results indicated that increasing hydrogen content percentage in the fuel blend leads to an increase in the amount of NOₓ in the released emissions and a substantial decrease in the CO and HC released emissions. Hamdan et al. [28] conducted an experimental study on a compression ignition (CI) engine using conventional diesel and hydrogen-diesel blended fuel. The results reported that the thermal efficiency and NOₓ emissions are increased with increasing the percentage of hydrogen in the blend. However, a significant reduction in particulate formation is observed. Rakopoulos et al. [29] examined the effect of mixing NG and hydrogen, and they claim that such blend in a direct injection engine combustion would be beneficial from the second-law of thermodynamics perspective. The exergy destruction associated with the
combustion process showed mitigation when increasing the percentage of hydrogen fraction in the injected fuel availability leading to an upsurge in the second-law efficiency.

2.1.2 Ammonia fueled ICE

Reiter and Kong [30] developed a method to supply ammonia in the intake manifold along with the injection of biodiesel or diesel fuel into the ICE cylinder. During the experiment, a maximum energy replacement of 95% was measured. In addition, increasing the supply of ammonia energy by 60% resulted in mitigation in the levels of the released NOx emissions. Kojima et al. [31] issued a patent discussing the use of ammonia as a fuel in ICEs; they used the heat emitted from the exhaust to generate hydrogen from ammonia, and the produced hydrogen will be stored. The stored hydrogen can be supplied to an auxiliary combustion chamber, the hydrogen after that can be combusted by a spark plug to assist in ammonia combustion in the primary combustion chamber. Ezzat and Dincer [32] proposed two energy systems as powering options for vehicle applications, the first one comprises liquefied ammonia tank, dissociation and separation unit (DSU) for thermal decomposition of ammonia and an internal combustion engine (ICE) to power the vehicle, hydrogen was produced on board and blended with ammonia for better engine performance. The second system is a hybrid system consisting of liquefied ammonia tank, DSC unit, a small ICE and a fuel cell system. In this system, hydrogen is produced on board and supplied to operate both the ICE and fuel cell system.

Dincer and Zamfirescu [33] introduce new ammonia fueled system for the vehicular application. The system comprises an ammonia tank, heat exchanger to heat the ammonia stream, decomposition and separation unit (DSU) with hydrogen and nitrogen conduits. The separated hydrogen from the DSU will be supplied to an internal combustion engine to achieve better performance. Numerous embodiments are also suggested by the authors. For instance, ammonia fueled hybrid system utilizing ammonia as fuel and using a homogeneous charge compression ignition engine (HCCI) for vehicle traction, heating, and air conditioning. Another embodiment is comprising an ammonia fuel cell system to produce power, heat, and refrigeration.
Frigo et al. [34] proved experimentally that adding hydrogen to an air-ammonia mixture will enhance the ignition and accelerate combustion eliminating the issues that are related to ammonia combustion such as; narrow flammability range, low flame temperature, and slow flame speed. Comotti and Frigo [35] developed a hydrogen generation system that is able to generate up to 1.4 Nm$^3$h$^{-1}$ of hydrogen on board from ammonia via the utilization of the thermal energy associated with the exhaust gasses using ammonia cracking reactor; the hydrogen is used to fuel an ICEs. However, higher combustion temperatures are observed causing higher NO$_x$ emissions.

Gross et al. [36] investigated the possibility of using ammonia/ dimethyl ether(DME) mixture as a fuel in a CI engine. Results showed that ammonia delayed the ignition and limits the engine load conditions because of its slow flame speed and high auto-ignition temperature. Moreover, higher CO, HC, NO$_x$ emissions occurred in the exhaust gases; the authors attribute this behavior to the presence of ammonia in the mixture, which leads to a reduction in the combustion temperature. However, increasing injection pressure up to 30 bar leads to better combustion and less harmful emissions. Ryu [37] investigated the emission and combustion characteristics of a CI engine using three different mixtures of ammonia and DME. Results show that the engine performance decreases with the increase of the ammonia concentration inside the fuel mixture. In addition, the increase in ammonia concentration caused a limitation in both the engine speed and power relative to 100% DME cases. Using ammonia as fuel will increase NO$_x$ emissions are increased due to the formation of fuel NO$_x$.

Ryu [38] investigated the effect of burning hydrogen produced by an ammonia dissociation catalyst on the performance and the released exhaust emissions of an ICE running on ammonia-gasoline fuel. Results showed that burning the obtained hydrogen can lead to an enhancement in the engine performance and mitigation in the harmful released flue gases. Moreover, utilization of the catalyst will reduce CO, HC, NH$_3$ and NO$_x$ emissions significantly. Mørch et al. [39] utilized metal ammine complexes as ammonia storage and tested the effect of utilizing a mixture of hydrogen/ammonia as a fuel for SI engine. The results proved that blending hydrogen with ammonia at a percentage of 10% by volume or 1% by mass fraction leads to a considerable improvement in the efficiency and the power
of the SI engine. Moreover, excess air ratio between 1.1 and 1.4 resulted in high NO\textsubscript{x} emissions.

**2.2 Using Solar Energy in Vehicles Applications**

Using solar energy in vehicle applications and implementing it effectively in vehicle powering options was always a promising field of research. For instance, ElNozahy and Salama [40] examined the practicality of using Photovoltaic (PV) electricity to charge PHEVs. Results showed that it is feasible to use PV for short period of time since it can partially fulfill the required energy for PHEVs charging. However, in the long operating periods, PV arrays will face difficulty to supply the increased demand of energy and storage devices should be implemented to fill the charging gap. Dinis et al. [41] used a computational application that allows investigating the influence of employing photovoltaic panels on board to electric vehicles. The application can calculate the number of kilometers covered by the vehicle and the corresponding amount GHG emissions associated with the electric power produced by the PV system. Ko and Chao [42] developed a quadratic maximization algorithm to enhance PV energy harvesting, particularly during the vehicle motion via the utilization of a maximum power point tracking method. The results showed a modification in the overall tracking efficiency. The results verified by the experimental data, which confirms the feasibility of using the proposed algorithm. Ezzat and Dincer [43] developed an integrated system consisting of PEM fuel cell, Li-ion battery and PV panels. The results showed that using photovoltaic panels can enhance the vehicle powering system efficiency. Moreover, PV panels were able to recover about 560 g of hydrogen if the vehicle were operated continuously for 3 hours at 118 kW. Kelly et al. [44] integrated PV powered high-pressure electrolyzer with Fuel cell system in an electric vehicle. The results showed that the irregular, fast alteration of solar power input caused by clouds didn’t influence the electrolyzer system response. Furthermore, changing the temperature from day to day didn’t affect the efficiency significantly. Moreover, the solar energy to hydrogen efficiency, electric to hydrogen efficiency and solar to electric efficiency averaged on 8.2%, 59.7% and 13.7% respectively. The system was able to generate up to 0.67 kg of hydrogen over a sunny and full day of operation. Furthermore, solar battery charging energy usage per mile basis is found to be three times more efficient compared to solar to hydrogen efficiency. Mebarki et al. [45] introduced a
supervisor control unit for an integrated PV- PEMFC- Battery system. The authors provided a mathematical model topology and carried out an identification for each subsystem. The Results show the feasibility of the hybrid system production for an electric vehicle.

2.3 Utilization of the Fuel Cells in Vehicles Applications

Many studies included thermodynamic modeling and comprehensive parametric studies on fuel cells fueled by hydrogen for vehicular applications. Zhang et al. [46] introduced a system comprising a PEM fuel cell and the internal combustion engine. The work aimed at recovering the excess unused hydrogen from the fuel cell and high-temperature heat accompanied with exhaust gasses from ICE and react to any peak power required during the vehicle motion. They recommended that if peak power is demanded instantly not only the flow of the fuel is enough, a mean of integration between both power suppliers is required. Sato et al. [47] presented a system consisting of an ethanol dehydrogenation catalytic reactor for producing hydrogen to supply both, a PEMFC to generate electricity for electric motors and a liquid by-product effluent from the reactor to be utilized as fuel for an ICE engine, or catalytically recycled to extract more hydrogen molecules. They claimed that the system could solve the issues of hydrogen production, distribution, and onboard storage. Andreasen et al. [48] designed a power traction system consisting of a lithium-ion battery pack and a high temperature PEMFC to extend the running range and act as an onboard charger to battery, they used a liquid methanol/water mixture of 60%/40% by volume, as fuel instead of compressed hydrogen, enabling a higher volumetric energy density. The system is investigated experimentally, and the fuel cell performed efficiently as a range extender and significantly increases the runtime and range of the vehicle powering system. Martin and Worner [49] studied the feasibility of using bioethanol and biodiesel to generate hydrogen onboard so it can be used as a fuel with high temperature PEM fuel cell. Two types of reformers are used, steam reforming and auto-thermal reforming. They concluded that hydrogen efficiency improved when preheating both feed water and feed air. Using auto-thermal reforming option for reforming of bioethanol and biodiesel are found to be better due to its less complexity. Corbo et al. [50] conducted an experimental investigation for a power system consists of a lithium-ion polymer battery and PEM fuel cell. The experimental work is carried out in steady state
condition. However, charge-discharge experiments are carried out to mimic the features of the application that is related to the automotive field. They also compared the performance of the lead-acid batteries with the lithium ion one, and the results came out in favorable to the lithium-ion batteries. A dynamic test is conducted using European R47 driving cycle and the system performed in a positive way. Xu et al. [51] performed theoretical modeling on a power system comprising lithium ion battery and PEM fuel cell. Results showed that within the working range of the electric motor, the maximum velocity, and driving distance are affected linearly by the different components parameters represented in the capacity of the battery, the mass of the available hydrogen, and fuel cell efficiency and power. Furthermore, accelerating time is found to be linearly influenced by the previous parameters except for the ones who are related to the battery. Moreover, Hydrogen consumption reduced by 14% when PEM efficiency witnesses an upsurge from 48.3% to 55%, and augmenting the braking energy ratio from 0% to 28% would lead to mitigation in hydrogen consumption by 16%. Hussain et al. [52] performed thermodynamic analysis based on energetic and exergetic approaches for a PEM fuel cell power system for light-duty vehicle accompanied with the comprehensive parametric study. The results displayed that increasing current density will lead to an upsurge in the difference between the gross stack power and net system power. In addition, both energetic and exergetic efficiencies of the system increased with increase stack operating temperature and pressure. Moreover, the air stoichiometry does not show a significant effect on energetic and exergetic efficiencies, and the most substantial exergy destruction rate took place in the fuel cell stack. Ay et al. [53] investigated the effects of changing the fuel cell operating temperature, current density, pressures of anode and cathode and membrane thickness on the PEM fuel cell exergetic performance. The results showed that PEM fuel cell exergy efficiency decreases with increasing current density and membrane thickness, and increases with increasing cell operating pressure. Kazim [54] investigated the effect of changing fuel cell operating temperatures, pressures, cell voltages and air stoichiometric on its exergetic performance. The results assert that increasing cell operating pressure and temperature, having higher cell voltage and increasing air stoichiometry (preferably between 2-4 to avoid the fuel cell membrane drying out at high operating temperatures) can cause a substantial improvement in the exergy efficiency of the PEMFC.
2.4 Ammonia Electrolyte Cells

Hydrogen can be produced onboard using ammonia electrolyte cell (AEC). Theoretically, Ammonia electrolysis consumes 95% lower energy compared to water electrolysis at same standard conditions [55]. The operation of the AEC unit is described as follows: liquid Ammonia is supplied to the AEC unit, on the cathode, hydrogen molecules are electrochemically produced by the ammonia reduction reaction as shown in the following reaction [56]:

$$3 \text{NH}_3 + 3e^- \rightarrow \frac{3}{2} \text{H}_2 + 3\text{NH}_2^-$$

On the anode, nitrogen molecules are electrochemically generated by the amide ions oxidation as follows:

$$3\text{NH}_2^- \rightarrow \frac{1}{2} \text{N}_2 + 2\text{NH}_3 + 3e^-$$

Consequently, the AEC overall reaction can be written as follows:

$$\text{NH}_3(\text{l}) \rightarrow \frac{1}{2} \text{N}_2(\text{g}) + \frac{3}{2} \text{H}_2(\text{g})$$

The overall reaction indicates that a theoretical voltage of 0.077 V is required to be supplied to the AEC at the ambient temperature and ammonia pressure of 10 bar to initiate the hydrogen production process. Boogs and Botte [57] integrated a micro proton exchange membrane fuel cell with AEC, the power produced from the fuel cell will be used to supply the AEC with the required energy to produce hydrogen onboard which in turn will be provided to the fuel cell for power production. They found that utilizing 203 L of aqueous ammonia can allow the vehicle to run around 483 km. Ezzat and Dincer [58] proposed an integrated energy system consisting of PEM fuel cell, photovoltaic panels, AEC unit, and a Li-ion battery. The photovoltaic panels are exploited to supply the AEC unit with the required power to generate hydrogen onboard to reduce the fuel cell hydrogen consumption and consequently the mileage of the introduced vehicle will increase. The AEC unit was able to produce 5.2 g/min of pure hydrogen at 10 bar on board.

Gwak et al. [59] conducted ammonia electrolysis experiments using zero gab cells, and it was proven that ammonia electrolysis technology is more efficient thermodynamically when compared with thermal decomposition as the activation energy for ammonia electrolysis was reported at 32.57 kJ/mol while the activation energy for thermal decomposition is ranging between 70-70 kJ/mol. Furthermore, pure hydrogen is generated
with the energy efficiency of over 80%. Goshome et al. [60] investigated the electrolysis of ammonia using NH₄Cl as an electrolyte under a current density of 70 mA/cm², hydrogen, and nitrogen are generated. Moreover, they successfully generated hydrogen at 20 MPa. Nevertheless, anode electrode corrosion observation is detected during the electrolysis process. They also concluded that metal (M) of an anode electrode is ionized in the ammonia solution forming metal chloride (MClₓ) instead of the primary oxidation reaction in the ammonia electrolysis process.

2.5 Thermoelectric Generators
Thermoelectric generator (TEG) is recognized and used to convert the thermal energy directly into electricity via the Seebeck effect. The Seebeck effect is a phenomenon that occurs when a temperature difference between two dissimilar metals generates a voltage difference between the two materials [61]. For instance, when thermal energy is supplied to one of the two semiconductors, the electrons that gain heat will transfer from the hot side towards the cold side. If the two semiconductors are connected via an electric circuit, direct current will be generated in the circuit. Although TEG efficiency is low, it can be utilized as a useful tool to recover the waste heat from the vehicle exhaust due to its simple design, require less maintenance, function at elevated temperatures, ease of operation, and it works in a clean manner without any harmful emissions. Moreover, extensive research in the thermoelectric materials fields has the potential to enhance the performance and conversion efficiency of the TEGs.

Although TEGs efficiency is low, it can be utilized to recover the waste heat from the vehicle exhaust due to their simple design, require less maintenance, function at elevated temperatures, ease of operation and it is operated in a clean manner without any harmful emissions. Moreover, innovation and improvement of thermoelectric materials can enhance the performance and conversion efficiency of the TEGs. Hussain et al. [62] introduced a model to the practicality of applying the concept of generating electricity from the exhaust gases using TEG unit. The authors succeeded to apply the model, and they carried out performance analysis using EPA highway driving cycle, and they were able to generate 400 W of electricity from the exhaust gases. Candadai et al. [63] reported a theoretical efficiency of 9.3% with ΔT of 240 between the hot and the cold side using a
Bi$_2$Te$_3$ based TEG with figure of merit of 1 at 298 K. Barma et al. [64] introduced new module, based on $p$-type (Bi,Sb)$_2$Te$_3$ and $n$-type hot forged Bi$_2$Te$_3$ that is able to produce 4.4 W and compared it with A Bi$_2$Te$_3$ based commercial module (HZ-2) that generates 3.7 W. They reported that the proposed TEG modules can achieve a thermal efficiency of 8.18% when $\Delta T= 240$. Liang et al. [65] introduced a mathematical model of two-stage TEG and compared it to the single stage TEG. The results show that the two stage TEG can achieve a conversion efficiency of 9.77% with total number of 30 thermocouples, 18 of them in the bottom stage. The conversion efficiency of two-stage TEG are found to be higher than the single-stage TEG.

Lee et al. [66] developed a mathematical model for TEG to assess temperature dependent performance represented in output power and efficiency. The results showed that augmenting leg spacing of the TEG decreases the thermal resistance leading to an upsurge in the amount of heat flow and the generated power and a reduction in the TEG conversion efficiency. Moreover, they found that actual figure-of-merit associated with thermal losses related to the thermoelectric material exhibits lower value compared to ideal figure-of-merit based on intrinsic material properties. Lan et al. [67] developed a dynamic model of TEG system designed to recover waste heat from vehicle exhaust. The simulation results show that 20% upsurge in the power output is achievable by optimizing the thermal contact conductance and the heat transfer coefficient of hot side heat exchanger.

2.6 Gas Turbines in Hybrid Vehicle Applications
Gas turbine hybrid vehicles comprise a micro gas turbine unit to generate electricity to supply the batteries with the required charging during vehicle operation. The gas turbine can also run in a steady mode and assist the battery in driving the vehicle. Gas turbine hybrid vehicles have many advantages such as; it comprises small numbers of rotating parts, the installation of the powering system does not require much space, gas turbine, and electric motor are known with their high power-weight ratio, the flexibility of fuels that can be used in the gas turbine [68]. Capata et al. [68] investigated the practicality of gas turbine hybrid vehicle system. The system comprises a gas turbine, electric motor and batteries, braking recovery system, and electric and mechanical storage devices such as capacitors and flywheels. The authors also investigated the feasibility of integrating ORC
to recover the waste thermal energy released from the gas turbine. The results showed that using R245fa as a working fluid in the ORC enable the ORC system to attain an efficiency of 8.73%. Sim et al. [69] developed a micro-power pack utilizing automotive alternators operated by a micro-gas turbine to recharge battery packs for electric vehicles application. Micro gas turbine efficiency is obtained via thermodynamic analysis of a simple Brayton cycle. The performance of the gas turbine is investigated through series of experiments at loading and no loading conditions. The results showed an upsurge in the mass and volumetric densities by 4 times and 5 times respectively. Shortlidge [70] reported the design, fabrication and the first round test of a 373 kW hybrid electric vehicle using two-spool, intercooled gas turbine engine with integral induction type alternators at which the gas turbine functions as the prime source of power for the vehicle. Capata and Sciubba [71] carried out theoretical and experimental analyses for a novel hybrid system utilizing gas turbine instead of ICE, the system consists of 100 kW battery back and two turbo gas set of 5 and 16 kW. The results show that the proposed system has all the potential to compete with the conventional ICE vehicle and Fuel cell powered vehicles. Christodoulou et al. [72] developed a new a gas turbine hybrid vehicle configuration comprising a micro-gas turbine, a battery bank, and a traction motor, the new configuration is aiming at mitigating fuel consumption and harmful emissions. The micro gas turbine is set to operate on a cyclic basis when the battery depth of charge reaches a value above 80%; the turbine will continue to operate until it provides full charges to the battery. The results showed that 23% saving in the fuel consumption is achievable. However, this percentage can drop if the system is applied in lightweight since the newly installed parts will add to the mass of the vehicle. However, in practice there is no commercialized production for gas turbine vehicles, many attempts have been made to produce gas turbine vehicles with no success. Some of the produced vehicles used gas turbine directly as the main powering source by meshing it with the mechanical drive system. This attempt was not successful because of the difficulty and complexity of meshing the gas turbine with the mechanical drive system and the steering system. The other direction of productions used the gas turbine as a range extender by operating and charging the batteries that are providing the electricity to the electric motor.
CHAPTER 3: SYSTEMS DESCRIPTION

Six integrated systems based on different powering options configuration are introduced in this chapter. The systems are developed for vehicle applications with the maximum obtainable power of 118 kW. The proposed integrated systems are described in details to demonstrate how they are functioning. The main powering options that are used in the introduced systems are internal combustion engines, fuel cells, batteries, PV, and gas turbines.

3.1 Base System and System 1.

Two systems are proposed in this section. The base system which is considered as a reference (base) system is shown in Fig. 3.1 while Fig. 3.2 displays the first developed integrated system which consists of Li-ion battery, fuel cell system, and photovoltaic arrays to supply the system with additional free renewable energy.

3.1.1 Base system

The system shown in Fig. 3.1 consists of Li-ion battery as a secondary power source, power control unit and electric motor with controller, PEM fuel cell stack module, which consists of the cooling cycle, air compressor, heat exchangers, and humidifiers. The compressor in the system module is used to pressurize air supplied to the fuel cell stack. Before entering the fuel cell stack, the pressurized air is cooled down through the heat exchanger and then humidified in humidifier 2 and enters fuel cell stack. Correspondingly, the hydrogen supplied from compressed hydrogen tank subjects to pressure reduction via a pressure regulator (Pr) to ensure hydrogen is provided at the desired operating conditions, then it passes through a humidifier 1 and enters the fuel cell stack. The excess hydrogen leaving from the fuel cell at state point 3 will be recirculated back at the entrance of humidifier 1.

The humidification of the inlet streams is an important process to avoid the dehydration of the membranes in the fuel cell stack, which leads to a deterioration in the PEM fuel cell performance. The primary function of the coolant system which is attached to the PEM fuel stack is to remove the heat produced from the stack due to the exothermic reaction of hydrogen and oxygen inside the fuel cell stack. The coolant system consists of circulating pump, heat exchanger 2, fan, and coolant; coolant is assumed to be (water/glycol). The PEM fuel cell stack will produce electricity and provide it to the power control unit (PCU),
which will supply it to the electric motor according to the different driving condition. The electric motor is connected to the front drive axle to provide the required traction for the vehicle. The extra electricity from the fuel cell will be utilized to charge the battery if needed.

3.1.2 System 1

Fig.3.2 depicts the schematic diagram of system 1. Note that, system 1 consists of the same components in the base system. However, in this system, photovoltaic arrays are incorporated and placed on the car roof, car hood, and car trunk to harness solar energy. The output electricity from the photovoltaic panels is supplied to the PCU, which in turn will supply it to the electric motor and reduce the required output power from the fuel cell and consequently reduce the hydrogen consumption. In this system, the traction of the vehicle is provided by the electric motor that is connected to the front drive axle.

Fig. 3.1 Schematic diagram of base system comprises fuel cell system and battery.

Research and development in the photovoltaic cells technology are flourishing every day, which enable for extra solar harnessing and additional electricity production for the same area of PV panels. For instance, a company developed a unique Fresnel lens that has the capability to focus sunlight towards the solar cells while augmenting the impact of the
sunlight by eight times. The system concept based on tracking the sun as it moves from east to west, drawing enough power from the sun through the concentrator each day to equal a four-hour battery charge (8 kWh) for the active surface area of 1.5 m² [73].

3.2 System 2
Fig. 3.3 displays the schematic diagram of system 2. System 2 has similar constituents to system 1. However, an ammonia electrolyte cell (AEC) and liquefied ammonia tank are added to the system. Liquefied ammonia enters AEC at state point 20; then the nitrogen gas will leave AEC from the anode at state point 22 and hydrogen gas will leave from the cathode at state point 23. Electricity required for the electrolysis process will be supplied directly from the PV arrays to the AEC unit. Hydrogen produced from the AEC passes through humidifier 3 then enters fuel cell stack at state point 25. A supplementary hydrogen tank of hydrogen is added to the system to store any unused hydrogen generated by the AEC when the vehicle is not operating.

Fig. 3.2 Schematic diagram of integrated system 1 comprises fuel cell system, Photovoltaic panels and Li-ion battery.
3.3 System 3

The system displayed in Fig.3.4 consists of ICE, which is the primary powering source and can generate up to a maximum traction power of 118 kW. The power generated from the ICE will be delivered to the front axle drive via a manual transmission system. The starting of the ICE will be initiated by the battery as shown in the figure. The ICE will be fueled with a blend of ammonia and hydrogen fuels with a mass ratio of 1% hydrogen to ammonia. Ammonia is supplied to the ICE from the liquid NH$_3$ tank placed at the rear of the vehicle. Liquefied ammonia leaves the tank and enters the pressure regulator at state point 1 so that the ammonia fuel is supplied to the ICE at the designated pressure of 2.5 bar. Ammonia abandons pressure regulator at state point 2, and the main stream will be divided into two streams. The first steam enters the ICE at state point 4 providing the ICE with the required ammonia fuel, while the second stream will be used in the ammonia thermal cracking process via the dissociation and separation unit (DSU). The heat required for the ammonia decomposition process will be provided by the high temperature exhaust gasses which leave the ICE. The exhaust gases enter the DSU at state point 8 and leave the DSU at state point 9. Ammonia inside the DSU will be decomposed and separated into hydrogen and nitrogen. Nitrogen is released into the air through state point 11. Hydrogen enters a heat exchanger at state point 6 so that its temperature can be reduced before it is supplied to the ICE and to provide a pre-heating process for the ammonia which enters the DSU unit. Hydrogen exits from the heat exchanger at state point 7 and enters the ICE to enhance the combustion process of ammonia.

3.4 System 4

The system presented in Fig.3.5 consists of ICE, ammonia DSU and PEM fuel cell and a battery to start the ICE. The vehicle traction power is shared between the ICE and the fuel cell; both powering sources will provide the vehicle with a maximum output power of 118 kW. Both the internal combustion engines and the electric motor are connected to the front drive axle via a gear train. The same installation mentioned in system 3 is duplicated in system 4. However, in system 4, a fuel cell system is hybridized with the ICE. A hydrogen purification unit (HPU) is added to eliminate any chance of ammonia contamination in the hydrogen stream leaving the DSU and supplying the fuel cell, which avoids any deterioration in the fuel cell performance.
Fig. 3.3 Schematic diagram of integrated system 2 comprises Fuel cell, Photovoltaic panels, Li-ion battery and AEC unit.

Fig. 3.4 Schematic diagram of system 3 comprises an ICE fueled with ammonia and hydrogen, and ammonia DSU unit for onboard hydrogen production.
Hydrogen leaving the HPU unit at state point 11 will be streamed to the gate of humidifier 1 and then to the fuel cell at state point 18, and any unused hydrogen by the fuel cell leaves from state point 19 and will be redirected to the gate of humidifier 1. The oxygen required for the electrochemical reactions inside the fuel cell will be provided by the compressed and humidified air that enters the fuel cell at state point 17. Heat exchanger 2 is utilized to reduce the temperature of the inlet air resulting from the compression process. Humidifiers 1 and 2 are used to prevent any dehydration in the PEM fuel cell that might cause a decline in the fuel cell performance. A coolant cycle is installed to remove the heat produced from the fuel cell stack due to the exothermic reaction, which occurs inside the fuel cell. PEM fuel cell will feed the power control unit with electricity so that it can be distributed to the electric motor and the other parasitic components inside the fuel cell system such as the compressor and the coolant circulating pump. In this system, the fuel cell is operating using the hydrogen produced on board from the ICE without the need to install any compressed hydrogen tanks in the system or the existence of any hydrogen refueling infrastructure.

Fig. 3.5 Schematic diagram of integrated system 4 comprises an ICE, PEM fuel cell and ammonia DSU.
3.5 System 5

Fig. 3.6 shows an integrated system comprises a liquefied ammonia tank, ICE, a TEG system and AEC unit and a battery for starting the vehicle. The power generated from the ICE will be delivered to the front axle drive via a manual transmission system. The liquefied ammonia that is stored in the tank at 20 °C and 9 bar will be supplied to the ICE at state point 4 after its pressure reduced to 2.5 bar via the pressure regulator (Pr) as displayed in Fig.3.6. The liquefied ammonia from the tank will be streamed to the AEC at state point3. At the beginning of the system operation, the battery can supply the AEC with required electricity to generate the hydrogen. As mentioned earlier only 1% hydrogen to ammonia ratio by mass can guarantee a satisfying engine performance. During the ICE operation, the exhaust gases released due to the combustion of ammonia and hydrogen with air will be directed to thermoelectric generator system at state point 5 and leaves the TEG at state point 8. The temperature difference between the hot and cold sides inside the TEG will produce electric power. TEG system will be cooled down using the vehicle cooling system; the cooling system will be designed to maintain a temperature difference of 250 degrees between the hot and cold side of the TEG.

Fig. 3.6 Schematic diagram of integrated system 5 comprises ICE, TEG and AEC unit.
The generated electricity from the TEG system will be supplied to the AEC at state point 9 along with the ammonia that will be provided from the ammonia tank and enters the AEC unit at state point 3. The electrochemical reaction will take place in the AEC unit resulting in electrochemical decomposition of ammonia and the release of nitrogen gas from the anode at state point 12 and the release of hydrogen gas from the cathode at state point 10. The hydrogen pressure will be reduced to 0.5 bar and will be supplied to the ICE.

3.6 System 6

Fig. 3.7 displays the schematic diagram of integrated system 6. In this system, a gas turbine and Li-ion battery will be used as the main powering sources for vehicle traction. The system consists of Li-ion battery, CNG tank, air compressor, combustion chamber, gas turbine, two generators, electric motor, PCU, TEG unit, ORC and an absorption chiller system. Although natural gas is a fossil fuel, it is used in this system because of its lower carbon dioxide emissions compared to other fossil fuels. Moreover, Natural gas is adopted in this system, to assert that this type of fuel can be used as a transitional solution, until the usage of carbon free fuels such as; hydrogen and ammonia is implemented in the transportation sector.

The Li-ion battery will be used to assist in vehicle powering during the startup of the vehicle and in the transition driving modes such as acceleration. As shown in Fig. 3.7, CNG leaves the tank towards the combustion chamber. Meanwhile, the air will be supplied to the compressor and pressurized up to 5 bar, and then it will be supplied to the combustion chamber. Compressed air and CNG will be mixed and combusted inside the combustion chamber. The exhaust gases released from the combustion chamber at state point 3 will strike the turbine and rotate it generating mechanical work that will be converted into electricity via the generator. The exhaust gases exit from the gas turbine at state 5 and enter a TEG unit at which additional electricity can be generated from the exhaust gases. To enhance the process of exhaust gases recovery, an ORC is installed in the introduced system. The ORC will be used to cool down the TEG unit and simultaneously the absorbed heat can be used to heat the ORC fluid. The ORC fluid will enter the expander at state point 8 and leaves the expander at state point 9 generating mechanical energy that will be converted to electric power via the generator that is connected to ORC expander. The
exhaust gases are leaving the TEG unit at state point 6 will be supplied to the absorption chiller system. Absorption chiller system consists of a generator, heat exchanger, absorber, condenser and evaporator at which the cooling effect to the vehicle cabin will be provided.

The electricity from TEG unit, ORC generator, and gas turbine generator will be supplied to the PCU. PCU will provide the obtained electricity to the electric motor that is connected to the front drive axle to drag the vehicle. PCU can also manage any additional generated electricity from gas turbine system to charge the Li-ion battery to achieve the optimum performance during vehicle driving.

Fig. 3.7 Schematic diagram of integrated system 6 comprises gas turbine, TEG, ORC and absorption chiller system to provide cabin cooling.
CHAPTER 4: SYSTEMS ANALYSES, MODELING AND SIMULATION

The thermodynamics analyses of the suggested systems will be based on energetic and exergetic approaches. Exergoeconomic concepts will be used to analyze the developed systems economically. The performances of the systems will be evaluated by determining the energy and exergy efficiencies for all of the introduced integrated systems. In this chapter, basic equations of energy and exergy will be introduced. The analysis of the main powering options will be described. In addition, equations of the dynamic analysis and the exergoeconomic analysis will be provided. Moreover, a section of the optimization study that is used in this thesis is included.

4.1 Thermodynamics Analysis
In this section, the mass, energy, entropy and exergy equations that can be used to analyze a control volume that includes interaction with heat, work, and mass with the surrounding environment will be stated. Thermodynamic analyses of the main components that are utilized in the proposed integrated system are also incorporated.

4.1.1 Mass Balance Equation
The general conservation of mass in a control volume for any system can be expressed as follows:

$$\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}} = \frac{dm}{dt}$$  \hspace{1cm} (4.1)

Here, \( \dot{m} \) denotes mass flow rate, and the terms “in” and “out” refer to the inlet and outlet of the control volume.

4.1.2 Energy Balance Equation
The conservation of energy equation can be obtained from the first law of thermodynamics as follow:

$$E_2 - E_1 = \delta Q - \delta W$$  \hspace{1cm} (4.2)

Here, \( E \), \( Q \), and \( W \) are the energy of the system, the heat, and work that the system exchange with the environment. The general energy balance equation can be presented as follows [74]:

32
\[ \dot{Q}_{cv} + \sum \dot{m}_{in} \left( h + \frac{u^2}{2} + gz \right)_{in} = \dot{W}_{cv} + \sum \dot{m}_{out} \left( h + \frac{u^2}{2} + gz \right)_{out} \] (4.3)

where \( z \) is the elevation, \( V \) is the velocity and \( h \) is the specific enthalpy.

### 4.1.3 Entropy Balance Equation and Entropy Generation

The entropy generation can be determined using the following equation:

\[ \sum \dot{m}_{in} s_{in} + \sum \frac{\dot{Q}_{cv}}{T} + \dot{S}_{gen} = \sum \dot{m}_{out} s_{out} \] (4.4)

where \( \dot{S}_{gen} \) refers to the entropy generation and \( s \) is the thermodynamics property entropy.

### 4.1.4 Exergy Balance Equation

Exergy is the maximum useful work that can be obtained from a process [75]. Exergy analysis is usually applied to detect the reasons of the thermodynamics irreversibilities which is named as exergy destruction. Which will enable a further improvement in the thermodynamic process. The exergy balance equation describing any system is presented as follows:

\[ \sum \dot{E}_{xQ} + \sum_{in} \dot{E}_{xflow} = \sum \dot{E}_{xw} + \sum_{out} \dot{E}_{xflow} + \dot{E}_{xd} \] (4.5)

where \( \dot{E}_{xQ} \) represents the exergy transfer rate. \( \dot{E}_{xflow} \) represents the exergy flow which transfer in or out of the system \( \dot{E}_{xw} \) refers to shaft work applied to or done by the system. And finally, \( \dot{E}_{xd} \) is the exergy destruction. The thermal exergy flow can be described as follows:

\[ \dot{E}_{xQ} = \left( 1 - \frac{T_0}{T_i} \right) \dot{Q} \] (4.6)

where \( (1 - T_0/T_i) \) where \( T_0 \) and \( T_i \) are ambient and system temperatures, respectively.

Exergy associated with work can be calculated as follows:

\[ \dot{E}_{xw} = \dot{W}_{cv} + P_0 \frac{dv_{cv}}{dt} \] (4.7)

where \( P_0 \) is the pressure of the dead state.

Exergy associated with a steady stream can be determined as follows:

\[ \sum_{in} \dot{E}_{xflow} - \sum_{out} \dot{E}_{xflow} = \sum_{in} \dot{m}_i e_{ix} - \sum_{out} \dot{m}_i e_{ix} \] (4.8)

There are four main components of the flow exergy; physical, chemical, potential and kinetic exergy.

\[ e_{xflow} = e_{xph} + e_{xch} + e_{xke} + e_{xpe} \] (4.9)

The physical exergy components are stated as follows:
\[ \text{ex}^{\text{ph}} = (h - h_0) - T_0 (s - s_0) \]  

(4.10)

Chemical exergy for a gaseous mixture can be written as follows:
\[ \text{ex}_{\text{mix}}^\text{ch} = \sum y_i \text{ex}_i^\text{ch} + RT_0 \sum y_i \ln y_i \]  

(4.11)

where \( y_i \) is the component mole fraction in the gas mixture.

Chemical exergy for liquid fuels can be written as follows:
\[ \varphi = 0.1882 \frac{h}{c} + 0.0432 \frac{o}{c} + 0.2169 \frac{s}{c} \left( 1 - 2.0628 \frac{h}{c} \right) + 1.0401 \]  

(4.12)

A simplification formula introduced by [76] for the calculation of the fuel chemical exergy is written below:
\[ \varphi = \frac{\text{ex}_{\text{fuel}}^\text{ch}}{\text{LHV}} \]

Chemical exergy ratio for any gaseous fuel containing carbon and hydrogen \( C_aH_b \) can be expressed as follows [98]:
\[ \varphi = 1.033 + 0.0169 \frac{b}{a} - \frac{0.0698}{a} \]  

(4.13)

Exergy destruction can be obtained from equation (4.5), or it can be calculated using entropy generation since \( \dot{\text{Ex}}_d \) changes linearly with it and can be determined using the following equation:
\[ \dot{\text{Ex}}_{d_i} = T_0 \cdot \dot{S}_{\text{gen}} \]  

(4.14)

The introduced integrated systems are analyzed thermodynamically, all the enthalpies, mass flow rates, pressures, exergies, and temperatures of the flows entering and leaving each system are identified and determined. Exergy destruction rates of the main components are also calculated to allocate the irreversible losses in each system. The mathematical modeling is executed utilizing the Engineering Equation Solver (EES) software. The following assumptions are taken into consideration while modeling the systems:

- The reference temperature \( T_0 = 298 \) K and reference pressure \( P_0 = 101.325 \) kPa.
- The variations in the kinetic and the potential energies and exergies are ignored.
- Any pressure loss in the heat exchangers, fuel cell system, AEC unit or other components is neglected, only the pressure losses in the pressure regulators are considered.
- The compressors, cooling pump, turbines, and fans operate adiabatically with an isentropic efficiency of 85%.
• The temperature difference between the hot and cold junction in the TEG is kept at 250, and an average figure of merit $ZT_{avg}$ value of 1.

• The working fluid in the cooling system of the fuel cell is ethylene glycol.

• The relative humidity of the inlet air and hydrogen is taken as 90%.

• A 20% of the produced heat is assumed to be lost by convection and radiation.

• The ICE maximum output power is 118 kW.

• The combustion occurs completely.

4.1.5 Photovoltaic system

The maximum power obtained from the photovoltaic system can be determined as follows:

$$P_m = V_m \times I_m$$  \hspace{1cm} (4.15)
where $V_m$ is the maximum voltage and $I_m$ is the maximum current.

The useable exergy rate leaving the PV system is calculated as follows:

$$E_{x_{PV}} = V_m \times I_m - \left[ \left( 1 - \left( \frac{T_0}{T_{cell}} \right) \right) \times (h_c \times A \times (T_{cell} - T_0)) \right]$$  \hspace{1cm} (4.16)
where $h_c$ is the convective heat transfer coefficient and defined as follows:

$$h_c = 5.7 + 3.8 \nu$$
where $\nu$ is the speed of the wind ($\text{m/s}$).

The maximum exergy rate entering PV system due to the solar radiation will be obtained as below:

$$E_{x_{so}} = \left( 1 - \frac{T_0}{T_{so}} \right) \times S_t \times A$$  \hspace{1cm} (4.17)
where $S_t$ is the global solar radiation in ($\text{W/m}^2$), and $A$ is the PV area in ($\text{m}^2$).

The main parameters considered in the modeling the PV system are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell operating temperature ($T_{cell}$)</td>
<td>46 °C</td>
</tr>
<tr>
<td>Effective area</td>
<td>3 m²</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>600 - 1200 W/ m²</td>
</tr>
<tr>
<td>Photovoltaic total output Energy</td>
<td>16 kWh</td>
</tr>
<tr>
<td>Temperature of the sun ($T_{so}$)</td>
<td>5227 °C</td>
</tr>
</tbody>
</table>
4.1.6 Internal combustion engine

The stoichiometric reaction for ammonia and hydrogen combustion can be written as follows:

\[
\text{NH}_3 + 0.75 \left( \text{O}_2 + 3.76 \text{N}_2 \right) \rightarrow 1.5 \text{H}_2\text{O} + 3.32 \text{N}_2 \tag{4.18}
\]

\[
\text{H}_2 + 0.5 \left( \text{O}_2 + 3.76 \text{N}_2 \right) \rightarrow \text{H}_2\text{O} + 0.5 \left( 3.76 \right) \text{N}_2 \tag{4.19}
\]

Mass balance equation for the ICE can be written as follows:

\[
\dot{m}_{\text{air}} + \dot{m}_{f} = \dot{m}_{\text{ex}} \tag{4.20}
\]

Energy balances equation for the ICE can be defined as follows:

\[
\dot{N}_{\text{air}} h_{\text{air}} + \dot{N}_{f} h_{f} = \dot{N}_{\text{ex}} h_{\text{ex}} + \dot{W}_{\text{ICE}} + \dot{Q}_{\text{loss,cool}} + \dot{Q}_{\text{loss,lub}} \tag{4.21}
\]

Exergy balance equation for the ICE can be expressed as follows:

\[
\dot{N}_{\text{air}} e_{\text{air}} + \dot{N}_{f} e_{f} = \dot{N}_{\text{ex}} e_{\text{ex}} + \dot{W}_{\text{ICE}} + E_{\text{loss,cool}}^Q + E_{\text{loss,lub}}^Q \tag{4.22}
\]

Here, \( \dot{W}_{\text{ICE}} \) refers to the power obtained from the ICE, \( \dot{Q}_{\text{loss,cool}} \) represents the heat loss to the cooling system, \( \dot{Q}_{\text{loss,lub}} \) refers to the heat loss in the friction and lubrication system in the ICE. \( E_{\text{loss,cool}}^Q \) refers to the exergy destruction rate in the ICE and \( E_{\text{loss,lub}}^Q \) are the heat associated with the thermal exergy for the cooling system and the lubrication system respectively and they can be calculated as follows:

\[
E_{\text{loss,cool}}^Q = \left( 1 - \frac{T_0}{T_{\text{cool,sys}}} \right) \dot{Q}_{\text{loss,cool}} \tag{4.23}
\]

\[
E_{\text{loss,lub}}^Q = \left( 1 - \frac{T_0}{T_{\text{lub,sys}}} \right) \dot{Q}_{\text{loss,lub}} \tag{4.24}
\]

Combustion properties of ammonia and hydrogen are shown in Table 4.2, the table incorporates data for hydrogen and ammonia molecular weights, stoichiometric air-fuel ratios, ignition limits, adiabatic flame temperatures, lower and higher heating values and standard chemical exergy.

4.1.7 Ammonia decomposition

The decomposition of ammonia can be written based on the dissociation fraction, \( x_d \), identifying the amount of each gas species in the product gas mixture by:

\[
\text{NH}_3 \xrightarrow{\frac{3x_d}{2}} \text{H}_2 + \frac{x_d}{2} \text{N}_2 + \left( 1 - x_d \right) \text{NH}_3 \tag{4.25}
\]
The heat essential for the reaction is given by [77] utilizing the enthalpy change of ammonia to increase its temperature to the designated level for decomposition, and the degree of the dissociation can be calculated by:
\[
\Delta h_{DSU}(T) = h(T) - h_0(T) + x_d \times \eta_d \times \Delta h_D(T)
\] (4.26)
where \(\Delta h_D\) is the heat required for the endothermic reaction of ammonia decomposition and \(\eta_d\) is the decomposition conversion efficiency. General operating features of the DSU unit are presented in Table 4.3.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Ammonia</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>NH(_3)</td>
<td>H(_2)</td>
</tr>
<tr>
<td>Molecular weight, (M_i) (kg/kmol)</td>
<td>17.03</td>
<td>2.016</td>
</tr>
<tr>
<td>Stoichiometric air-fuel ratio (kmol air/kmol)</td>
<td>3.57</td>
<td>2.387</td>
</tr>
<tr>
<td>Stoichiometric air-fuel ratio (kg air/kgi)</td>
<td>6.05</td>
<td>34.2</td>
</tr>
<tr>
<td>Ignition limits (%-vol. in air)</td>
<td>16-25</td>
<td>4-75</td>
</tr>
<tr>
<td>Adiabatic flame temperature, (°C)</td>
<td>1803</td>
<td>2110</td>
</tr>
<tr>
<td>Auto ignition temperature, (°C)</td>
<td>651</td>
<td>571</td>
</tr>
<tr>
<td>Lower heating value, (MJ/kg)</td>
<td>18.61</td>
<td>119.95</td>
</tr>
<tr>
<td>Higher heating value, (MJ/kg)</td>
<td>22.5</td>
<td>141.6</td>
</tr>
<tr>
<td>Standard chemical exergy, (MJ/kg)</td>
<td>119.52</td>
<td>20.29</td>
</tr>
</tbody>
</table>

Source [78]

Table 4.3 DSU features

<table>
<thead>
<tr>
<th>Chemical Reaction Equation</th>
<th>NH(_3) → 1/2 N(_2) + 3/2 H(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Enthalpy of Reaction, (\Delta h_{NH_3}) (kJ/mol)</td>
<td>45.90</td>
</tr>
<tr>
<td>Operating Temperature, (T_{DSU}) (°C)</td>
<td>400-700</td>
</tr>
</tbody>
</table>

**4.1.8 Thermoelectric generator**

Energy balance for the TEG system in system 5 can be expressed as follows:
\[
\dot{m}_7 h_7 + \dot{m}_6 h_6 = \dot{m}_9 h_9 + \dot{m}_8 h_8 + \dot{W}_{TEG}
\] (4.27)
Exergy balance across the thermoelectric devices in system 5 can be written as follows:
\[
\dot{m}_7 e_7 + \dot{m}_6 e_6 = \dot{m}_9 e_9 + \dot{m}_8 e_8 + \dot{W}_{TEG} + \dot{E}_{x_{TEG}}
\] (4.28)
The maximum output power obtained from the TEG system can be calculated as follows [79]:

37
\[
\frac{\dot{W}_{\text{max}}}{K \times T_c} = \frac{(1-\theta)^2 \times ZT_{\text{avg}}}{20 \times (1+\theta)}
\]  
(4.29)

Here, \( \theta = \frac{T_c}{T_h} \) and it refers to the ratio between the temperature of the TEG cold side and the temperature of the TEG hot side.

The overall reduced thermal conductivity of the thermoelectric generator “K” can be determined as follows:

\[
K = A_p \times \frac{k_p}{L_p} + A_n \times \frac{k_n}{L_n}
\]  
(4.30)

The material of TEG is chosen to be bismuth telluride for both the “p” and “n” sides with a thermal conductivity of 1.2 W/m².K.

4.1.9 Absorption chiller system

The heat supplied to the generator in the absorption chiller system can be defined as follows:

\[
\dot{Q}_{\text{Gen}} = \dot{m}_4 (h_4 - h_9)
\]

The outlet condition of the generator can be obtained by applying the following energy and exergy balance equations:

\[
\dot{Q}_{\text{Gen}} + \dot{m}_{16} h_{16} = \dot{m}_{10} h_{10} + \dot{m}_{17} h_{17}
\]  
(4.31)

\[
\dot{Q}_{\text{Gen}} \left(1 - \frac{T_0}{T_{s_{\text{Gen}}}} \right) + \dot{m}_{16} e_{x16} = \dot{m}_{10} e_{x10} + \dot{m}_{17} e_{x17} + E\dot{x}_{\text{dGen}}
\]  
(4.32)

The cooling effect which takes place in the evaporator of absorption chiller cycle can be obtained using the following equations:

\[
\dot{Q}_{\text{eva2}} = \dot{m}_{13} (h_{13} - h_{12})
\]  
(4.33)

\[
\dot{Q}_{\text{eva2}} \left(1 - \frac{T_0}{T_{s_{\text{eva2}}}} \right) + \dot{m}_{12} e_{x12} = \dot{m}_{13} e_{x13} + E\dot{x}_{\text{deva2}}
\]  
(4.34)

4.1.10 Components used in the systems

The additional components that are utilized in the different integrated systems can be analyzed energetically and exergetically Table 4.4. The components included in the table are pressure regulator, expander, and compressor, for each component mass, energy, entropy and exergy balance equations are listed.
Table 4.4 Energy, entropy and exergy analyses of some parts used in the systems.

<table>
<thead>
<tr>
<th>Component</th>
<th>Component name</th>
<th>Balance equation</th>
</tr>
</thead>
</table>
| 1         | Pressure regulator | MBE: \( \dot{m}_1 = \dot{m}_2 \)  
EBE: \( \dot{m}_1 h_1 = \dot{m}_2 h_2 \)  
EnBE: \( \dot{m}_1 s_1 + \dot{S}_{\text{gen}} = \dot{m}_2 s_2 \)  
ExBE: \( \dot{m}_1 \text{ex}_1 = \dot{m}_2 \text{ex}_2 + \dot{\text{Ex}}_{\text{Dest}} \) |
| 1         | Expander       | MBE: \( \dot{m}_1 = \dot{m}_2 \)  
EBE: \( \dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W}_{\text{out}} \)  
EnBE: \( \dot{m}_1 s_1 + \dot{S}_{\text{gen}} = \dot{m}_2 s_2 \)  
ExBE: \( \dot{m}_1 \text{ex}_1 = \dot{m}_2 \text{ex}_2 + \dot{\text{Ex}}_{\text{Dest}} + \dot{W}_{\text{out}} \) |
| 1         | Compressor     | MBE: \( \dot{m}_1 = \dot{m}_2 \)  
EBE: \( \dot{m}_1 h_1 + \dot{W}_{\text{in}} = \dot{m}_2 h_2 \)  
EnBE: \( \dot{m}_1 s_1 + \dot{S}_{\text{gen}} = \dot{m}_2 s_2 \)  
ExBE: \( \dot{m}_1 \text{ex}_1 + \dot{W}_{\text{in}} = \dot{m}_2 \text{ex}_2 + \dot{\text{Ex}}_{\text{Dest}} \) |

4.2 Electrochemical modeling

This section includes the electrochemical models that are used to analyze the fuel cell system and the ammonia electrolyte cell.

4.2.1 Fuel cell model

The fuel cell total output voltage can be determined by the following equation [13,80]:

\[
E = E_r - E_{\text{act}} - E_{\text{ohm}} - E_{\text{conc}} \tag{4.35}
\]

where \( E \) denotes the practical cell potential, \( E_r \) is the reversible cell potential, \( E_{\text{act}} \) is the activation losses, \( E_{\text{ohm}} \) is the ohmic losses and \( E_{\text{conc}} \) is the concentration losses.

The reversible cell potential with liquid water as a byproduct can be obtained utilizing Nernest equation as follows [80]:

\[
E_r(T,T) = 1.482 - 0.000845 T + 4.31 \times 10^{-5} T \ln(p_{H_2} p_{O_2}^{0.5}) \tag{4.36}
\]

Here, \( T \) is the cell operating temperature, and \( P_i \) denotes for the selected species partial pressure.

The activation can be calculated for the anode and the cathode utilizing the equations below:

\[
E_{\text{act}} = E_{\text{act, an}} + E_{\text{act, ca}}
\]
\[ E_{\text{act,an}} = \frac{RT_{FC}}{\alpha_{\text{an}nF}} \ln \left( \frac{J}{J_{0,\text{an}}} \right) \]  

(4.37)  

\[ E_{\text{act,ca}} = \frac{RT_{FC}}{\alpha_{\text{ca}nF}} \ln \left( \frac{J}{J_{0,\text{ca}}} \right) \]  

(4.38)  

Here, \( J \) is the current density (A/cm²), \( J_0 \) is the exchange current density (A/cm²). \( n \) is the number of electrons involved, \( R \) is the universal gas constant (KJ/kmol.K), \( F \) is the Faraday’s constant (C/mol), \( \alpha_{\text{an}} \) and \( \alpha_{\text{ca}} \) are the anode and cathode electron transfer coefficient correspondingly. The subsequent empirical equation can be utilized to determine the exchange current density \( J_0 \) values at any operating temperature [81].  

\[ J_0 (T) = 1.08 \times 10^{-21} \times \exp \left( 0.086 \times T_{FC} \right) \]  

(4.39)  

The ohmic losses are occurred due to the membrane resistance to the flow of the protons. The resistance of the fuel cell membrane is only considered and can be calculated using the following equations:  

\[ E_{\text{ohm}} = J R_{\text{ohm}} \]  

(4.40)  

\[ R_{\text{ohm}} = \frac{\delta_{\text{mem}}}{\sigma_{\text{mem}}} \]  

(4.41)  

\[ \sigma_{\text{mem}} = (0.005139 \lambda_{\text{mem}} - 0.00326) \times \exp \left[ 1268 \frac{1}{303} - \frac{1}{T_{FC}} \right] \]  

(4.42)  

\[ \lambda_{\text{mem}} = \begin{cases} 
0.043 + 17.81a - 39.85a^2 + 39.85a^3, & 0 < a \leq 1 \\
14 + 1.4(a - 1), & 1 < a \leq 3 
\end{cases} \]  

(4.43)  

\[ a = \frac{x_{\text{H}_2\text{O}}}{P_{\text{sat}}} \]  

(4.44)  

Here, \( \sigma_{\text{mem}} \) is the conductivity of the membrane (Ω⁻¹ cm⁻¹), \( \lambda_{\text{mem}} \) is the membrane water content. The membrane conductivity can significantly change by altering the temperature and water content [82], \( a \) is the membrane water activity, and \( X_{\text{H}_2\text{O}} \) is the inlet water mole fraction.  

The concentration losses can be determined at the anode and cathode electrodes, and it typically happens as a result of the mass transfer limitation at elevated current densities.  

\[ J_{L,\text{an}} = \frac{2 F P_{\text{H}_2\text{O}D_{\text{an}}^{\text{eff}}}}{RT \delta_{\text{an}}} \]  

(4.45)  

\[ J_{L,\text{ca}} = \frac{4 F P_{\text{O}_2D_{\text{ca}}^{\text{eff}}}}{(p-P_{\text{O}_2})RT \delta_{\text{ca}}} \]  

(4.46)  

Here, \( J_{L,\text{an}} \), \( D_{\text{an}}^{\text{eff}} \), \( J_{L,\text{ca}} \) and \( D_{\text{ca}}^{\text{eff}} \) are the anode and cathode limiting current density and effective diffusion coefficient respectively.
Consequently, the concentration losses can be expressed as follows:

\[ E_{conc} = -\frac{RT}{2F} \ln \left( 1 - \frac{J}{J_{L,an}} \right) + \frac{RT}{2F} \ln \left( 1 + \frac{P_{H_2} J}{P_{H_2O} J_{L,an}} \right) - \frac{RT}{4F} \ln \left( 1 - \frac{J}{J_{L,ca}} \right) \]  

(4.47)

The amount of power that can be produced by every single cell can be calculated using the equation below:

\[ \dot{W}_{cell} = E(I) \times J \times A_{cell} \]  

(4.48)

Here, \( J \) is the current density and \( A_{cell} \) is the geometric cell area. The overall stack power can be calculated by the equation below:

\[ \dot{W}_{stack} = n_{fc} \times \dot{W}_{cell} \]

where \( n_{fc} \) is the number of cells in the fuel cell stack. The fuel cell net obtained work can be identified as follows:

\[ \dot{W}_{Fc} = \dot{W}_{stack} - \dot{W}_{comp} - \dot{W}_{cp} - \dot{W}_{fan} \]  

(4.49)

Table 4.5 displays all the parameters and the corresponding values that are utilized in the electrochemical model of the fuel cell system. Parameters values for current density, cell area, hydrogen and oxygen stoichiometry, membrane thickness are obtained from similar studies that utilize PEMFC in vehicular applications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density</td>
<td>1150 mA/cm²</td>
</tr>
<tr>
<td>Cell area</td>
<td>900 cm²</td>
</tr>
<tr>
<td>Hydrogen stoichiometry</td>
<td>1.2</td>
</tr>
<tr>
<td>Oxygen stoichiometry</td>
<td>2</td>
</tr>
<tr>
<td>Cell operating temperature</td>
<td>30 - 80 °C</td>
</tr>
<tr>
<td>Cell operating pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Net power</td>
<td>98.32 kW</td>
</tr>
<tr>
<td>No of cells</td>
<td>180</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>-10 – 50 °C</td>
</tr>
<tr>
<td>Reference pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Membrane thickness</td>
<td>0.0183 cm</td>
</tr>
<tr>
<td>Tank normal operating pressure</td>
<td>700 bar</td>
</tr>
<tr>
<td>Storage Density (Capacity)</td>
<td>5.7% weight</td>
</tr>
<tr>
<td>Hydrogen Storage mass</td>
<td>5 kg</td>
</tr>
</tbody>
</table>

Source [52,54,80]
4.2.2 AEC model

The overall theoretical energy that is essential for hydrogen generation comprised of two portions, Δg which stands for the electrical demand and TΔs which reflect the heat demand, and it can be assessed as:

\[ \Delta h = \Delta g + T\Delta s \]  

(4.50)

Here, Δg is the Gibbs free energy change of reaction; T is the absolute temperature, and Δs is the change in entropy.

The molar flow rate of the hydrogen that can be obtained from the AEC unit can be calculated by:

\[ \dot{N}_{H_2,\text{out}} = \frac{I_{\text{AEC}}}{3F} \]  

(4.51)

The theoretical electrolysis voltage of liquid NH₃ at any temperature can be calculated using Nernst's equation [83]:

\[ E^{\text{r, AEC}} = -\frac{\Delta G^o}{3F} + \frac{RT^{\text{AEC}}}{3F} \ln\left( \frac{P_{N_2}^{0.5} P_{H_2}^{1.5}}{P_{H_2}} \right) \]  

(4.52)

where \( P_{H_2} \) is the partial pressure of H₂, and \( P_{N_2} \) is the partial pressure of N₂.

The required electrolysis voltage can be calculated by adding all the AEC resistances (activation, concentration, ohmic) to reversible cell voltage as expressed in the following equation:

\[ E^{\text{AEC}} = E^{\text{r, AEC}} + E^{\text{act, AEC}} + E^{\text{ohm, AEC}} + E^{\text{conc, AEC}} \]  

(4.53)

The ohmic resistance can be expressed as follows:

\[ E^{\text{ohm, AEC}} = \rho \delta J^{\text{AEC}} \]  

(4.54)

where \( \rho \) is the material resistivity and \( \delta \) is the element thickness. The ohmic resistance for all the AEC components can be determined as follows:

\[ E^{\text{ohm, AEC}} = \left( \rho_{\text{an}} \delta_{\text{an}} + \rho_{\text{ca}} \delta_{\text{ca}} + \rho_{\text{e}} \delta_{\text{e}} \right) J \]  

(4.55)

where the subscripts (an, ca, e) stand for the anode, cathode, and electrolyte material respectively [13].

The activation resistance can be calculated for the anode and the cathode utilizing the equations below:

\[ E^{\text{act, AEC}} = E^{\text{act, an}} + E^{\text{act, ca}} \]
\[ E_{\text{act,an}} = \frac{RT_{\text{AEC}}}{nF} \sinh^{-1} \left( \frac{J}{2J_{0,\text{an}}} \right) \]  
(4.56)

\[ E_{\text{act,ca}} = \frac{RT_{\text{AEC}}}{nF} \sinh^{-1} \left( \frac{J}{2J_{0,\text{ca}}} \right) \]  
(4.57)

The concentration losses can be determined at the anode and cathode electrodes by the following equations:

\[ E_{\text{conc,ca}} = \frac{RT}{nF} \ln \left[ \left( 1 + \frac{JRT_{\text{AEC}} \delta_{\text{ca}}}{nF D_{\text{NH}_3} \overline{P}_{\text{H}_2}} \right) \left( 1 - \frac{JRT_{\text{AEC}} \delta_{\text{ca}}}{nF D_{\text{NH}_3} \overline{P}_{\text{NH}_3}} \right) \right] \]  
(4.58)

\[ E_{\text{conc,an}} = \frac{RT}{nF} \ln \left[ \left( 1 + \frac{JRT_{\text{AEC}} \delta_{\text{an}}}{nF D_{\text{N}_2} \overline{P}_{\text{N}_2}} \right)^{0.5} \right] \]  
(4.59)

Here, \( D_{\text{eff}} \) refers to the effective diffusion coefficient. Consequently, the overall concentration resistance can be expressed as follows:

\[ E_{\text{conc,AEC}} = E_{\text{conc,an}} + E_{\text{conc,ca}} \]

The power required by the AEC for the electrolysis process unit can be determined as follows:

\[ P_{\text{El,AEC}} = J_{\text{AEC}} E_{\text{AEC}} A_{\text{cell}} n_{\text{cells}} \]  
(4.60)

Table 4.6 shows all the parameters and the corresponding values that are utilized in the electrochemical modeling of the AEC unit. Parameters values for current density, anode, cathode and electrolyte thickness, cell operating temperature are taken from studies that modeled and tested AEC performance experimentally.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density</td>
<td>250 mA/cm²</td>
</tr>
<tr>
<td>Exchange current density</td>
<td>0.037 mA/cm²</td>
</tr>
<tr>
<td>Cell operating temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Cell operating pressure</td>
<td>10 bar</td>
</tr>
<tr>
<td>No of cells</td>
<td>83</td>
</tr>
<tr>
<td>Anode thickness</td>
<td>0.0020</td>
</tr>
<tr>
<td>Cathode thickness</td>
<td>0.0020</td>
</tr>
<tr>
<td>Electrolyte thickness</td>
<td>0.0040 cm</td>
</tr>
<tr>
<td>Ammonia tank capacity</td>
<td>15 L</td>
</tr>
<tr>
<td>Liquefied ammonia temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Liquefied ammonia pressure</td>
<td>10 bar</td>
</tr>
</tbody>
</table>

Source [84,85]
4.3 Energy Efficiencies

This section is comprising energy efficiency definitions for the primary subsystems in the proposed integrated systems. Energy efficiency can be defined as the useful output energy generating from the system divided by the total energy input entering the system.

The Energy efficiency of the PV system can be expressed as follows:

$$\eta_{PV} = \frac{V_m \times I_m}{S_t \times A}$$  \hspace{1cm} (4.61)

The energy efficiency of the ICE can be written as follows:

$$\eta_{ICE} = \frac{W_{ICE}}{N_{air} h_{air} + N_{F} h_{F}}$$  \hspace{1cm} (4.62)

The energy efficiency of the TEG system can be calculated by the following equation [86]:

$$\eta_{TEG} = \frac{W_{TEG}}{N_{7} h_{7} - N_{9} h_{9}} = \frac{T_h - T_c}{T_h} \times \frac{\sqrt{1+ZT-1}}{\sqrt{1+ZT+\frac{T_c}{T_h}}}$$  \hspace{1cm} (4.63)

The COP of the absorption cooling system can be expressed as follows:

$$\text{COP}_{en,AbC} = \frac{Q_{eva}}{N_{4} h_{4} + N_{9} h_{9}}$$  \hspace{1cm} (4.64)

The energy efficiency of the fuel cell system can be determined as follows:

$$\eta_{sys,FC} = \frac{W_{FC}}{N_{f} \times h_{f}}$$  \hspace{1cm} (4.65)

The energy efficiency of the AEC unit can be defined as follows:

$$\eta_{AEC} = \frac{N_{H_{2}} h_{H_{2}}}{N_{N_{H_{3}} h_{N_{H_{3}}} + W_{TEG}}}$$  \hspace{1cm} (4.66)

The energy efficiency of system 1 can be calculated as follows:

$$\eta_{sys,1} = \frac{W_{net} + V_{m} \times I_{m} + Bp_{dis}}{N_{3} h_{3} - N_{4} h_{4} + S_t \times A + Bp_{cha}}$$  \hspace{1cm} (4.67)

The energy efficiency of system 2 can be determined as follows:

$$\eta_{sys,2} = \frac{W_{net2} + N_{23} h_{23} + Bp_{dis}}{N_{3} h_{3} - N_{4} h_{4} + S_t \times A + N_{20} h_{20} + Bp_{cha}}$$  \hspace{1cm} (4.68)

The energy efficiency of system 3 can be expressed as follows:

$$\eta_{sys,3} = \frac{W_{ICE} + Q_{Dis}}{N_{2} h_{2}}$$  \hspace{1cm} (4.69)

The energy efficiency of system 4 can be written as follows:

$$\eta_{sys,4} = \frac{W_{ICE} + W_{FC}}{N_{2} h_{2}}$$  \hspace{1cm} (4.70)

The energy efficiency of system 5 can be defined as follows:
\[ \eta_{\text{sys},5} = \frac{\dot{W}_{\text{ICE}} + \dot{W}_{\text{TEG}}}{N_3 h_3} \]  
(4.71)

The energy efficiency of system 6 can be calculated as follows:
\[ \dot{W}_{\text{net}} = \dot{W}_{\text{turb}} + \dot{W}_{\text{TEG}} + \dot{W}_{\text{ORC}} - \dot{W}_{\text{comp}} \]
\[ \eta_{\text{sys},6} = \frac{\dot{W}_{\text{net}} + q_{\text{ca,cool}}}{N_2 h_2} \]  
(4.72)

### 4.4 Exergy Efficiencies

The exergy analysis can provide an insightful evaluation of any energy system, and it can predict the thermal characteristics of any energy system accurately [87]. In this section, overall exergy efficiencies of the introduced integrated systems along with the exergy efficiency definitions for the main units in the integrated systems will be provided.

The exergy efficiency of the PV system can be expressed as follows:
\[ \psi_{\text{PV}} = \frac{V_m \times I_m - [(1 - \frac{T_0}{T_{\text{cell}}}) \times (h_c \times A \times (T_{\text{cell}} - T_0))] \times (1 - \frac{T_0}{T_{\text{SO}}}) \times S_t \times A}{N_f \times e_x} \]  
(4.73)

The exergy efficiency of the ICE can be expressed by the following equation:
\[ \psi_{\text{ICE}} = \frac{\dot{W}_{\text{ICE}}}{N_f \times e_x} \]  
(4.74)

The exergy efficiency of the TEG system can be calculated as below:
\[ \psi_{\text{TEG}} = \frac{\dot{W}_{\text{TEG}}}{N_{\text{in}} \times e_{\text{in}} - N_{\text{out}} \times e_{\text{out}}} \]  
(4.75)

The exergetic COP of the absorption cooling system can be expressed as follows:
\[ \text{COP}_{\text{ex,AbC}} = \frac{Q_{\text{eva}} \times (1 - \frac{T_0}{T_{\text{eva}}})}{N_4 \times e_x} \]  
(4.76)

The exergy efficiency of the fuel cell system can be determined as follows:
\[ \psi_{\text{sys,fc}} = \frac{\dot{W}_{\text{fc}}}{N_f \times e_x} \]  
(4.77)

The exergy efficiency of the AEC unit can be defined as follows:
\[ \psi_{\text{AEC}} = \frac{N_{\text{H}_2} \times e_{\text{H}_2}}{N_{\text{NH}_3} \times e_{\text{NH}_3} + \dot{W}_{\text{TEG}}} \]  
(4.78)

The exergy efficiency of system 1 can be calculated as follows:
\[ \psi_{\text{sys,1}} = \frac{\dot{W}_{\text{net}} + V_m \times I_m - [(1 - \frac{T_0}{T_{\text{cell}}}) \times (h_c \times A \times (T_{\text{cell}} - T_0))] \times (1 - \frac{T_0}{T_{\text{SO}}}) \times S_t \times A + B_{\text{p,dis}}}{N_3 \times e_x - N_4 \times e_x + \frac{1}{N_3 \times e_x} + (1 - \frac{T_0}{T_{\text{cell}}}) \times S_t \times A + B_{\text{p,cha}}} \]  
(4.79)
Given that the inputs and outputs are both electricity for electrical storage systems, the energy and exergy efficiencies can be considered the same [88], the specification and date that are used to calculate $P_{b\text{dis}}$ and $P_{b\text{ch}}$ are shown in Table 4.7.

Table 4.7 Battery Specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>173 V</td>
</tr>
<tr>
<td>Battery discharge power</td>
<td>20 kW</td>
</tr>
<tr>
<td>Battery charge/discharge efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Cell</td>
<td>48</td>
</tr>
<tr>
<td>Dimensions</td>
<td>$611 \times 318 \times 100$ mm</td>
</tr>
<tr>
<td>Weight</td>
<td>24 kg</td>
</tr>
<tr>
<td>Rated capacity</td>
<td>5.5 Ah</td>
</tr>
</tbody>
</table>

Source [89]

Exergy efficiency of system 2 can be calculated as follows:

$$
\Psi_{sys,2} = \frac{W_{\text{net}_2} + N_{23}e_{23} + Bp_{\text{dis}}}{N_{3}e_{3} - N_{4}e_{4} + S_{1}A + N_{20}e_{20} + Bp_{\text{cha}}} \quad (4.80)
$$

Exergy efficiency of system 3 can be expressed as follows:

$$
\Psi_{sys,3} = \frac{W_{\text{ICE}} + Q_{Ds_u}}{N_{2}h_{2}} \left(1 - \frac{T_{0}}{T_{dsu}}\right) \quad (4.81)
$$

Exergy efficiency of system 4 can be identified as follows:

$$
\Psi_{sys,4} = \frac{W_{\text{ICE}} + W_{\text{FC}}}{N_{2}e_{2}} \quad (4.82)
$$

Exergy efficiency of system 5 can be defined as follows:

$$
\Psi_{sys,5} = \frac{W_{\text{ICE}} + W_{\text{TEG}}}{N_{3}e_{3}} \quad (4.83)
$$

Exergy efficiency of system 6 can be calculated as follows:

$$
W_{\text{net}} = W_{\text{turb}} + W_{\text{Teg}} + W_{\text{ORC}} - W_{\text{comp}}
$$

$$
\Psi_{sys,6} = \frac{W_{\text{net}} + E_{\text{ca,cool}}}{N_{2}e_{2}} \quad (4.84)
$$

4.5 Dynamic Analysis

For further detailed analysis, longitudinal dynamic modeling is required to evaluate the system performance such as maximum speed, gradeability and accelerating time [90].
Moreover, the performance of two of the proposed integrated system will be assessed using WLTP, which designed by experts under the guideline of the UNEC. This test procedure comprises a collection of data points for the speed versus time for a vehicle traveling on a specific route. The engine performance characteristics, such as power and torque and mean effective pressure (MEP) using the following equations [90]:

\[
\dot{W}_{\text{ICE}} = \frac{n_{\text{ICE}} \times \eta_v \times N_e \times V_d \times \rho_a \times Q_{HV}}{N_r \times \left(\frac{A}{F}\right)} \quad (4.85)
\]

\[
\text{Tor}_{\text{ICE}} = \frac{n_{\text{ICE}} \times \eta_v \times V_d \times \rho_a \times Q_{HV}}{2 \times \pi \times N_r \times \left(\frac{A}{F}\right)} \quad (4.86)
\]

\[
\text{MEP} = \frac{n_{\text{ICE}} \times \eta_v \times \rho_a \times Q_{HV}}{\left(\frac{A}{F}\right)} \quad (4.87)
\]

Here, \(\eta_v\) is the volumetric efficiency, \(N_e\) refers to the engine speed per second, \(Q_{HV}\) is the fuel heating value, \(V_d\) is the engine displacement, \(\rho_a\) refers to air density, \(\left(\frac{A}{F}\right)\) is the air/fuel ratio and \(N_r\) is the number of revolution per cycle and it’s equal to 2 for four stroke engine.

The equation of motion for the vehicle in the longitudinal direction can be expressed as:

\[
\sum F_x - (F_{RA} + F_{RR} + F_{RG}) = M_d \frac{du}{dt} \quad (4.88)
\]

Here, \(F_x\) refers to the tractive force, \(F_{RA}, F_{RR}, F_{RG}\) represent the air resistance, rolling resistance and gradient resistance respectively. \(M_d\) and \(u\) are the vehicle dynamic mass and its longitudinal speed respectively.

Tractive force at different gear reductions can be expressed as follows:

\[
F_x = \frac{\eta_m \times \eta_d \times \beta_i \times \beta_d}{r_T} \times T_{\text{ICE}}(\omega_e) \quad (4.89)
\]

where \(\eta_g\) and \(\eta_d\) refer to the gearbox transmission efficiency and differential efficiency respectively. \(\beta\) is the reduction ratio and subscripts \(i\) and \(d\) represent number a of gear ratio and differential respectively. \(r_T\) is the tire radius.

Air resistance, rolling resistance and gradient resistance can be calculated using the following equations:

\[
F_{RA} = \frac{1}{2} \rho_a \times C_d \times A_f \times u^2, \quad F_{RR} = \mu \times W_V, \quad F_{RG} = W_V \times \sin(\alpha_{\text{road}}) \quad (4.90)
\]

Here, \(C_d, A_f, u\) are the coefficient of drag, vehicle frontal area and vehicle speed respectively. \(\mu_R\) and \(W_V \alpha_{\text{road}}\) are the rolling coefficient, vehicle weight and road gradient angle respectively. Maximum vehicle speed can be obtained graphically by plotting the
tractive force and the total resistance force versus the vehicle speed. The intersection point between the tractive force and the total resistance will represent the maximum speed.

The maximum vehicle gradeability can be calculated as follows:

$$\alpha_{\text{road}, \text{max}} = \sin^{-1} \left( \frac{\eta_g \times \eta_d \times \beta_1 \times \beta_d \times T_{\text{ICE}, \text{max}}}{r_d \times V_w} - \mu_R \right)$$

(4.91)

Fig. 4.1 shows the torque and power map characteristics of the electric motors that can be installed in systems 1, 2, 6. The figure displays the variation of the electric motor maximum torque and continuous torque with the electric motor rpm. The maximum obtainable torque is recorded at 385 N.m, while the maximum continuous torque is recorded at 165 N.m. The maximum continuous torque and maximum torque are found to be declining when the electric motors rpm exceeds 5000 rpm. This figure also shows the alteration of the electric motor maximum power and continuous power with the electric motor rpm. The maximum obtainable power is recorded at 156 kW, while the maximum continuous power is recorded at 93 kW. At the beginning of the motion and during the driving on low speed inside the city, higher torque is required.

![Torque and power map](image)

Fig. 4.1 Power and torque map for the electric motors that can be installed in system 1, 2 and 6, adapted from [91].

However, at high speeds, for instance, during the driving on the high way, the vehicle requires more power, which interprets the increase of the obtained power at high electric
motors rpm. The power torque map of this traction motor is published by the manufacturer, and additional details can be found in [91]. Fig.4.2 demonstrates the torque and power map characteristics of the electric motor that can be used in systems 4, at which the electric motor maximum torque and continuous torque is plotted with the electric motor rpm. The maximum torque is found to be 360 N.m, while the maximum continuous torque is recorded at 205 N.m. Fig.4.2 also displays the change in the electric motor maximum power and continuous power with electric motor speed. The maximum electric motor can attain 125 kW, while the maximum continuous power ca reach 70 kW. The power torque map of this electric motor is released by the manufacturer, and more information can be found in [92].

![Power and torque map for the electric motors that can be installed in system 4, adapted from [92].](image)

Table 4.8 shows all the parameters that are used in the dynamic analysis of systems 3 and 5. Dynamic analysis is adopted for system 3 and 5 because these systems can be adopted as immediate alternatives for the conventional ICE that are using petroleum fuels with only minor modifications in the fuel injection and ignition systems inside the current ICE.
Table 4.8 Data utilized in the dynamic analysis of system 3 and system 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder stroke, $H$</td>
<td>0.09007 m</td>
</tr>
<tr>
<td>Cylinder bore, $D$</td>
<td>0.09018 m</td>
</tr>
<tr>
<td>Displacement volume $V_{dis}$</td>
<td>2.3 L</td>
</tr>
<tr>
<td>Gross vehicle Weight for system 3, $W_V$</td>
<td>2225 kg</td>
</tr>
<tr>
<td>Gross vehicle Weight for system 5, $W_V$</td>
<td>2250 kg</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>11</td>
</tr>
</tbody>
</table>
| Stoichiometric air-to-fuel ratio (kg/kg)           | Ammonia 6.05  
Hydrogen 34.2 | |
| Stoichiometric air-to-fuel ratio (kmol/kmol)       | Ammonia 3.57  
Hydrogen 2.387 | |
| First gear ratio, $\beta_1$                       | 3.643                      |
| Second gear ratio, $\beta_2$                      | 2.080                      |
| Third gear ratio, $\beta_3$                       | 1.361                      |
| Fourth gear ratio, $\beta_4$                      | 1.024                      |
| Fifth gear ratio, $\beta_5$                       | 0.83                       |
| sixth gear ratio, $\beta_6$                       | 0.686                      |
| Differential ratio, $\beta_d$                     | 4.105                      |
| Tire type                                         | P245/60 R18 105H           |
| Tire rolling radius, $r_T$                        | 0.4124 m                   |
| Rolling resistance coefficient, $\mu$             | 0.015                      |
| Drag coefficient, $C_{dr}$                        | 0.3                        |
| Air density, $\rho_a$                             | 1.225 kg/m³               |
| Vehicle frontal area, $A_f$                       | 2.1 m²                     |
| Differential efficiency, $\eta_d$                 | 100%                       |
| Mechanical efficiency, $\eta_m$                   | 90 %                       |
| Volumetric efficiency, $\eta_v$                   | 95%                        |
| Road friction coefficient, $\varphi$              | 0.98                       |

Source [21,93–96]
4.6 Exergoeconomic Analysis

The exergoeconomic analysis can provide deeper analysis as it combines both economic principles and exergy analysis to produce a cost-effective system which can’t be achieved if the system analyzed exergetically or economically alone [97]. Selecting the ratio of the rate of thermodynamic loss to capital cost is one of the vital principles for system analysis based on the approaches of thermoeconomic. The aim of performing exergoeconomic analysis can be listed as follows [97]: determining the cost of all the products included in the system, determine the flow costs lines in the system and optimize the overall system.

The parameter $\dot{C}$ ($$/s$$) is defined as flow cost for each system flow stream. The cost balance can be simply explained as the cost of all inlet exergy streams in addition to the capital cost, Operation and maintenance costs which should be equivalent to the cost of the existing exergy streams [98]:

$$\sum_{in} \dot{C}_k + \dot{C}_{Q,k} + \dot{Z}_k = \sum_{out} \dot{C}_k + \dot{C}_{w,k}$$  \hspace{1cm} (4.92)

where $\sum_{in} \dot{C}_k$, $\sum_{out} \dot{C}_k$ represents total costs of exergy flows entering and leaving the component. $\dot{Z}_k$ is representing the summation of the capital cost and cost of maintenance and operations of the component and $\dot{C}_{w,k}$ is the total costs associated with work. The cost of exergy flow can be described as follows:

$$\dot{C}_k = c_k \dot{Ex}_k$$  \hspace{1cm} (4.93)

where $c$ is given in $$$/kWh and $\dot{Ex}$ is given in kW. The capital costs of any part is expressed as $\dot{Z}$ in $$/h. $\dot{Z}$ can be calculated using the following equation:

$$\dot{Z} = \frac{TCC}{t_{oper}}$$  \hspace{1cm} (4.94)

Here, $TCC$ denotes the total cost of the component and it considers both the capital cost and cost of operation and maintenance and $t_{oper}$ is overall number of component operational hours. $TCC$ can be calculated as follows:

$$TCC = CRF (CC + OM)$$  \hspace{1cm} (4.95)

Here, CRF represents the capital recovery factor, and OM represents the operational and maintenance costs and they can be expressed by the following equations:

$$CRF = \frac{i (1+i)^n}{(1+i)^n -1}$$  \hspace{1cm} (4.96)

$$OM = CC \times OM_{ratio}$$  \hspace{1cm} (4.97)
where I refer to the rate of interest and n represents the number of years at which the system is expected to be operating and $OM_{ratio}$ can be determined based on the material and application of the component.

The exergy destruction cost rate for each part can be determined using the following equation:

$$\dot{C}_D = c \times \dot{Ex}_d$$  \hspace{1cm} (4.98)

Total cost rate of the system or any component can be determined by adding exergy destruction cost rate and overall capital and operational cost of the system or the component as follows:

$$\dot{C}_{tot} = \dot{C}_D + \dot{Z}$$  \hspace{1cm} (4.99)

The smaller the value of $\dot{C}_{tot}$, the more cost effective the component or the system. Thus, equation (4.99) is adopted as an objective function for minimizing cost of system components in the optimization study.

The exergoeconomic factor can be utilized as an indicator of the effectiveness of the system based on the cost and can be calculated as follows:

$$f = \frac{\dot{Z}}{\dot{Z} + \dot{C}_D}$$  \hspace{1cm} (4.100)

The exergoeconomic balance equations of the main parts that are used in the integrated systems can be expressed as follows:

- **PV**

$$\dot{Ex}_{in \ c_{in}} + \dot{Z}_{PV} = \dot{Ex}_{ele \ PV \ c_{ele \ PV}} + \dot{Ex}_{heat \ c_{heat}} + \dot{Exd}_{PV \ c_{PV \ Exd}}$$  \hspace{1cm} (4.101)

- **Fuel cell**

$$\dot{Ex}_{air \ in \ c_{air \ out \ c_{air}}} + \dot{Ex}_{H2 \ in \ c_{H2 \ out \ c_{H2}}} = \dot{Ex}_{air, out \ c_{air}} + \dot{Ex}_{H2O \ in \ c_{H2O \ out \ c_{H2O}}} + \dot{W}_{FC \ c_{W}} + \dot{Ex}_{heat \ c_{heat}} + \dot{Exd}_{FC \ c_{FC \ Exd}}$$  \hspace{1cm} (4.102)

- **ICE**

$$\dot{Ex}_{air \ c_{air}} + \dot{Ex}_f = \dot{Ex}_{ex \ c_{ex}} + \dot{W}_{ICE \ c_{W}} + \dot{Ex}_{cool \ c_{cool}} + \dot{Exd}_{ICE \ c_{ICE \ Exd}} + \dot{Ex}_{lub \ c_{lub}}$$  \hspace{1cm} (4.103)
• TEG
\[
\dot{E}_{\text{ex,in}} c_{\text{ex}} + \dot{E}_{\text{x,in}} c_{\text{w}} = \dot{E}_{\text{ex,out}} c_{\text{ex}} + \dot{E}_{\text{x,out}} c_{\text{w}} + W_{\text{TEG}} c_{\text{w}} + \dot{E}_{\text{d,TEG}} c_{\text{TEG,Exd}} 
\]
(4.103)

• AEC
\[
\dot{E}_{\text{x,NH}_3,\text{in}} c_{\text{NH}_3} + \dot{W}_{\text{ele,AEC}} c_{\text{ele,AEC}} = \dot{E}_{\text{x,H}_2} c_{\text{H}_2} + \dot{E}_{\text{x,N}_2} c_{\text{N}_2} + \dot{E}_{\text{d,AEC}} c_{\text{AEC,Exd}}
\]
(4.104)

The cost rate of solar radiation entering PV system, water and heat produced from the fuel cell, Nitrogen produced from AEC and any supplied air without compression power are assumed to be zero.

The results of the exergoeconomic analysis are presented in the results and discussion chapter. The parameters that are used in the exergoeconomic study are shown in Table 4.9. The table includes the interest rate and the operational life time that are used in the calculations, operational and maintenance cost is taken as 2.2% of the capital cost. Systems annual operational hours is taken as 294 h based on the information from a driving survey [99].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interest rate</td>
<td>7%</td>
</tr>
<tr>
<td>Lifetime of all components</td>
<td>10 years</td>
</tr>
<tr>
<td>Cost of hydrogen in 2017</td>
<td>108.37 $/GJ</td>
</tr>
<tr>
<td>Cost of pressurized ammonia at 10 bar</td>
<td>10.64 $/GJ</td>
</tr>
<tr>
<td>Calculated capital recovery factor</td>
<td>0.1424</td>
</tr>
<tr>
<td>Systems annual operation hours</td>
<td>294 h</td>
</tr>
<tr>
<td>Operational and maintenance percentage of capital cost</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Source [77,99,100]

### 4.7 Optimization Study

The optimization of an energy system provides modifications to the system assembly and design parameters and enhance system efficiency depending on one or more specified design objectives. Topology optimization is a mathematical technique that enhances the layout of the material inside a specified design space for pre-known boundary conditions.
and constraints in order to improve the system performance to the highest possible value. This method is distinguished from other methods of optimization by the fact that the design is able to achieve any shape inside the space of the design. The typical topology optimization formulations utilize the method of finite elements as a tool to assess the performance of the design. The optimization of the design is optimized by exploiting gradient based mathematical programming techniques like the algorithm of optimality criteria or nongradient-based algorithms such as genetic algorithms. Numerous applications in the field of biochemical, aerospace, civil engineering, and mechanical engineering can be optimized using this method of optimization. Presently, the topological optimization is adopted at the concept level of a design process. However, the outcome of the optimization is sometimes not possible to be manufactured due to the natural presence of the free forms. Therefore, the final results from this method are fine-tuned to be possible for manufacturing. Nonetheless, direct manufacturing of the results obtained from the topology optimization is possible utilizing additive manufacturing. Hence this method can be considered as a crucial part of the design for additive manufacturing.

Optimizing multiple objectives in the system would provide the system with better design variables that would help in design the system in an optimal way. For instance, increasing exergy efficiency and reducing fuel consumption as possible, maximizing the profit and reducing the minimum cost and minimizing the GHGs emission. [101]. In this thesis, the objective function for the multi-objective optimization comprises the exergy efficiency to be maximized and total cost rate of the system to be minimized. The first step in performing the optimization study is to identify the system boundaries and the effective operating parameters. For integrated energy systems, the process can be broken into optimization of the subsystems. After that comes identifying the optimization criteria. This may include energy, economic or environmental criteria. Selection of the decision variables is the following step. These are the variables based on which the optimization process is performed. These variables must be selected independent and represent the characteristics of the studies system. They also must be selected from the variables that affect the system performance and cost. Next step is the selection of an appropriate mathematical model of optimization. In this study, the evolutionary genetic algorithm will be utilized for
performing the optimization study. An evolutionary algorithm for optimization is inspired by mechanisms of biological evolution, such as reproduction, mutation, recombination, and selection. There are different methods of the evolutionary algorithm as an artificial neural network, fuzzy logic, and genetic algorithm, which will be utilized in this study. Optimal solution generated from the genetic algorithm is based on the evolutionary techniques of inheritance, learning, natural selection, and mutation. During this process, each individual of the population is evaluated with respect to its fitness, which is governed by the defined objective function. Based on their fitness, multiple individuals are picked and modified using mutation technique, to produce a new population. A genetic algorithm is utilized because no initial conditions are needed, it can function with numerous design variables targets global optima (as opposed to local optima), uses populations (as opposes to individuals), and exploits objective function formation (as opposed to derivatives).

The optimization process is carried out utilizing Engineering Equation Solver software (EES). In the optimization tool in EES, the lower and upper bounds need to be assigned to each selected independent variable, bounds need to be selected carefully to enhance the chance of obtaining an optimum value. All the critical parameters that could have a substantial influence on the system performance and cost are required to be incorporated into the optimization study. However, the limitation associated with some variables must be considered as constraints in any design problem and in the optimization study. Notably, in the algorithm utilized in this thesis since the initial population and succeeding stochastic selections are taken from the range of the value specified in the lower and upper bounds of the different parameters. Seven objective functions will be considered in this study, six objective functions will be representing the exergy efficiencies of the different integrated systems, and they are defined in details in section 4.4, and all the function will be targeted for maximization. The seventh optimization function considers the total cost rate of each system and can be expressed as follows:

$$\hat{C}_{total,sys\,i} = \hat{Z}_{Total,sys\,i} + \hat{C}_{D,Total,sys\,i} \quad (4.105)$$

Here, $i$ represents system number and this equation will be applied for each system to identify the total cost rate of the system, this function will be targeted for minimization.
In this study, the genetic algorithm optimization is carried out for 64 generations; the maximum mutation rate is taken as 0.2625 with 16 individuals representing the populations. The low mutation rate is chosen to prevent the algorithm from searching for an optimum at locations far from the current optimum and focus the research near the current optimum. There are more parameters that can be changed in the generic algorithm. Nonetheless, they are fixed and not adjustable in the EES software. The exergy efficiencies for each integrated system are individually optimized to be the maximum possible value. The total cost rates obtained from each system are also individually optimized to have the lowest value to reduce the cost of the system. Eventually, for each system, the exergy efficiency equation and the total cost rate equation are combined in a function, at which the exergy efficiency is divided by the total cost rate and the function is set to be maximized. The constraints of some selected variables are shown in Table 4.10, at which the upper and lower bounds are set based on the available date from previous studies.

Table 4.10 Constraints of some selected design variables used in the optimization study

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower</th>
<th>Upper</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature, $T_0$</td>
<td>-10</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Fuel cell temperature, $T_c$</td>
<td>-10</td>
<td>100</td>
<td>°C</td>
</tr>
<tr>
<td>Fuel cell current density, $J_{Fc}$</td>
<td>400</td>
<td>1500</td>
<td>mA/cm²</td>
</tr>
<tr>
<td>Fuel cell active area, $A_{Fc}$</td>
<td>300</td>
<td>1200</td>
<td>cm²</td>
</tr>
<tr>
<td>AEC current density, $J_{AEC}$</td>
<td>100</td>
<td>600</td>
<td>mA/cm²</td>
</tr>
<tr>
<td>AEC active area, $A_{AEC}$</td>
<td>300</td>
<td>900</td>
<td>cm²</td>
</tr>
<tr>
<td>AEC temperature, $T_{AEC}$</td>
<td>-10</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Solar irradiance, $I_{Sc}$</td>
<td>600</td>
<td>1200</td>
<td>W/m²</td>
</tr>
<tr>
<td>Area of PV, $A_{pv}$</td>
<td>2</td>
<td>3.5</td>
<td>m²</td>
</tr>
<tr>
<td>Interest rate, $i$</td>
<td>2</td>
<td>10</td>
<td>%</td>
</tr>
<tr>
<td>Lifetime</td>
<td>5</td>
<td>20</td>
<td>years</td>
</tr>
</tbody>
</table>

Source [52–54,57,60,80,85,102–104]
CHAPTER 5: RESULTS AND DISCUSSION

In this chapter, the results obtained from the proposed integrated systems modeling are presented and assessed comparatively. This chapter comprises a base system and system 1 results, results obtained from system 2, results of systems 3 and 4, and results obtained from systems 5 and 6. The results of the exergoeconomic analysis and optimization study are also included. Finally, a comparison between the introduced integrated is carried out.

The mathematical modeling of the integrated systems is executed using the Engineering Equation Solver (EES) software. The major advantage of the EES is that it incorporates high accuracy thermodynamic and transport property database for hundreds of substances in a manner that permits it to be utilized with the equation solving capability, which makes it very useful for the engineers that are working in the field of thermodynamics. The EES also comprises the parametric tables that permit the user to relate a number of variables at a time. The parametric tables can also be utilized to create plots. Moreover, the EES software has an integrated optimization tool that can be used to optimize the modeled systems without the need to move the obtained data to different software to carry out the optimization study. Moreover, the ADVISOR software is used to calculate the weight of the different introduced systems.

5.1 Base System and System 1 Results

The performance aspects of the base system and system 1 are investigated by a comprehensive study covering energy and exergy analyses. Numerous operating conditions, reference state parameters, and system parameters are altered to examine their effects on the performance of system 1. Furthermore, the effect of exploiting photovoltaic panels in system 1 on hydrogen consumption is evaluated. The derived theoretical model of the fuel cell system is validated by comparing the results of the current study with the data available in the open literature. Fig. 5.1 shows the comparison of the experimental data taken from [105] and theoretical data from [106] with the results of the present study. It is evident from the figure that the results of the current model are in agreement with the experimental and theoretical data from the above mentioned references. Moreover, Fig. 5.2 shows another validation curve for the present fuel cell model with theoretical and
experimental data from [107,108] and the results indicate that the present model fits with the results obtained from both of them.

Fig. 5.1 Comparison of the polarization profiles for model verification purposes with experimental data obtained from [105] and theoretical data from [106].

Fig. 5.2 Comparison between the polarization profiles for model verification purposes, model is verified with theoretical data obtained from [107] and experimental data from [108].
Fig. 5.3 shows the relation between the actual voltage, ohmic overpotential, concentration overpotential, activation overpotential and power density for the fuel cell model used in the base system. Actual voltage shows declination from 0.843 to 0.2 V when increasing current density from 100 to 1600 mA/cm². This is mainly due to the increase in the values of the activation overpotential from 0.3198 to 0.464 V, values of concentration overpotential from 0.0009545 to 0.585 V, and the values of the ohmic overpotential from 0.0126 to 0.2014 V. However, power density increased from 0.08436 W/m² at a current density of 100 mA/cm² reaching a maximum value of 0.8218 W/m² at a current density of 1523 mA/cm² and then it decreases to 0.7425 W/m² at a current density of 1600 mA/cm².

Fig. 5.3 Effect of changing current density on fuel cell actual voltage, power density and fuel cell ohmic, concentration and activation overpotential for the fuel cell system.

Fig. 5.4 shows the effect of varying fuel cell hydrogen consumption on fuel cell exergy destruction and overall energy and exergy efficiencies of system 1. Exergy destruction increased from 0.669 to 133.9 kW when increasing hydrogen consumption by the fuel cell from 0.6488 to 129.8 g/min. However, system 1 energy efficiency decreases from 60.55% to 45.94% with the increase in the hydrogen consumption by fuel cell from 0.6488 to 129.8 g/min. Moreover, exergy efficiency decreases from 62.2 to 46.35% with the upsurge in the fuel cell hydrogen consumption from 0.6488 to 129.8 g/min. The reduction in the exergy destruction...
efficiency is mainly due to the surge in the hydrogen consumption by the fuel cell which leads to an additional fuel cell power output and consequently more exergy to be destroyed. Fig. 5.5 shows the influence of altering fuel cell current density on exergy destruction, energy and exergy efficiencies and total power output of system 1. The overall energy and exergy efficiencies of system 1 decreased from 60.95 to 37.7 % and from 61.66 to 38.04 % with the increase in the fuel cell current density from 100 to 1600 mA/cm². However, system net output power witnesses an increase from 11.53 kW at 100 mA/cm² to a maximum value of 110.6 kW at a current density of 1424 mA/cm² then it declines to 108.9 kW at a current density of 1590 mA/cm². Additionally, exergy destruction of fuel cell increased from 8.067 to 189.1 kW with the upsurge of the fuel cell current density from 100 to 1600 mA/cm²; this behavior occurs due to the increment in the internal losses of the fuel cell. The reason behind the declination of the total energy and exergy efficiencies is the significant increase of the exergy destruction of the fuel cell compared to the net output power increase.

Fig. 5.4 Effect of changing mass flow rate entering fuel cell on exergy destruction of fuel cell and overall energy and exergy efficiencies of system 1.

Fig. 5.6 depicts the effect of changing fuel cell current density on overall energy and exergy efficiencies of the base and first systems. Increasing the current density from 100 mA/cm²
to 1500 mA/cm² leads to a decline in both of the energy and exergy efficiencies from 53.2 to 37.13% and from 60.72 to 37.73% for the base system respectively. While for system 1 it decreases from 60.95 to 37.7% and from to 61.66 to 38.04% respectively. The exergy efficiencies of the base system and system 1 showed higher values compared to energy efficiencies of the base system and system 1. However, system 1 energy and exergy efficiencies display higher values compared to energy and exergy efficiencies of the base system. This behavior can be interpreted by the addition of photovoltaic arrays to system 1, which enhances the overall energy and exergy efficiencies of system 1.

Fig. 5.5 Effect of changing current density on fuel cell exergy destruction, net power output and overall system energy and exergy efficiencies for system 1.

Fig.5.7 shows the effects of changing solar radiation on overall energy and exergy efficiencies of system 1. It is observed that increasing the solar radiation from 600-1200 W/m² leads to an insignificant upsurge in the overall exergy and energy efficiencies from 45.86 to 46.01% and from 46.26 to 46.43 % respectively. The increase in the energy and exergy efficiencies can be interpreted by the increase in the power output of the PV system due to the upsurge in the solar insolation. However, the increase in both efficiencies values is not significant due to the low installed PV power compared to the system output power.
Fig. 5.6 Effect of changing fuel cell current density on overall energy and exergy efficiencies of the base and first system.

Fig. 5.7 Effect of changing solar radiation on overall energy and exergy efficiencies of system 1.
Fig. 5.8 displays the effect of increasing the ambient temperature on energy and exergy efficiencies of the base and first systems. The energy efficiencies of the base system and system 1 remain constant since changing the ambient temperature has no influence on it. This is mainly due to the fact that the ambient temperature is not inherent in any of the energy efficiency calculations. Nevertheless, increasing the ambient temperature causes an insignificant decrease in the exergy efficiencies of the base system and a minimal increase in the exergy efficiency of system 1. The slight increase in the exergy efficiency of system 1 is due to the slight increase in the PV exergy input into the system from 1.782 to 2.027 kW.

![Graph showing the effect of ambient temperature on energy and exergy efficiencies for base system and system 1 and exergy PV input to the system.]

Fig. 5.8 Effect of changing the ambient temperature on the overall energy and exergy efficiencies for base system and system1 and exergy PV input to the system.

Fig. 5.9 demonstrates the effect of varying hydrogen consumption rate on the net power output of base system and system 1. Comparing hydrogen consumption for the two systems with the corresponding output power shows the reduction that occurs in hydrogen consumption rate in system 1 due to the utilization of photovoltaic cells. It is observed that system 1 attained the same maximum output power of 118 kW at lower hydrogen consumption rate of 2.285 g/s compared to the hydrogen consumption rate of 2.336 g/s for the base system as shown in Fig. 5.10, recovering 0.052 g/s of hydrogen fuel which could...
save 561 g of hydrogen during 3 hours of continuous driving at the max driving power of 98.32 kW, which is approximately 10 % of the hydrogen storage tank used in the proposed systems.

Fig. 5.9 Effect of changing hydrogen consumption rate on net power output for both systems.

Fig. 5.10 Hydrogen consumption rate for the base system and system 1 at the same net output power of 118 kW, magnified from Fig.5.9.
Fig. 5.11 shows the influence of changing fuel cell operating temperature on fuel cell exergy destruction, output power and overall system energy and exergy efficiencies of the base system and system 1. It is observed that increasing the operating temperature from 20 to 80 °C reduces the exergy destruction of the fuel cell from 150 to 120.8 kW. The reduction in the exergy destruction rate can be interpreted by the fact that increasing fuel cell operating temperature leads to a mitigation in the internal losses of the fuel cell. Moreover, the total exergy efficiencies of the base and first systems showed an increase from 37.55 to 47.16% and from 37.92 to 47.41% respectively when increasing the operating temperature from 20 to 80 °C. Furthermore, the energy efficiencies of the base and first systems show an upsurge from 36.98 to 46.17% and from 37.77 to 46.95% respectively when increasing the operating temperature from 20 to 80 °C. Furthermore, the fuel cell output power showed an augmentation from 78.25 to 100.3 kW for the same variation range of the fuel cell operating temperature.

Fig. 5.11 Effect of changing fuel cell operating temperature on fuel cell exergy destruction, output power and overall system energy and exergy efficiencies for the base system and system 1.

Fig. 5.12 show the effect of varying the interest rate on the total cost rate of system 1 and its exergoeconomic factor. Increasing the interest rate from 2 to 15% results in an increase in the exergoeconomic factor from 29.74 to 38.4%. Moreover, for the same variation in the
interest rate the total cost rate of system 1 increased from 57.14 to 79.21 $/h. Fig. 5.13 displays the influence of varying system lifetime on both the exergoeconomic factor and total cost rate of system 1. Augmenting the expected operational life of the system from 5 to 20 years results in a reduction in the exergoeconomic factor of the system from 41.18 to 27.24% while the total cost rate reduced from 90.4 to 52.89 $/h. This behavior can be interpreted by the fact that increasing the plant operational life will eventually lead to a lower overall system cost.

![Graph](image)

**Fig. 5.12** Effect of varying the interest rate on the exergoeconomic factor and total cost rate of system 1.

The single objective optimization results for the exergy efficiency of system 1 are demonstrated in Table 5.1. Moreover, the results sensitivity are included, and it is carried out by altering the decision variable by 20%. The highest exergy efficiency for system 1 is found to be 57.84%. Fuel cell area and current density are found to be closer to the lower bound; this is mainly because the mitigation in the fuel cell current density leads to an increase in the fuel cell system efficiency. Solar radiation is found to be closer to the upper bound along with the PV area which will definitely enhance system efficiency.
Fig. 5.13 Effect of varying the system lifetime on the exergoeconomic factor and total cost rate of system 1.

Table 5.1 Single objective optimization results for the exergy efficiency of system 1 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area&lt;sub&gt;FC&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>300</td>
<td>57.84</td>
<td>300</td>
<td>480</td>
<td>57.2</td>
</tr>
<tr>
<td>Area&lt;sub&gt;PV&lt;/sub&gt; (m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>3.184</td>
<td>57.7</td>
<td>3.484</td>
<td>3.5</td>
<td>57.85</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>57.84</td>
<td>0.02123</td>
<td>0.04723</td>
<td>57.84</td>
</tr>
<tr>
<td>Current density (mA/cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>400</td>
<td>57.85</td>
<td>400.8</td>
<td>620.8</td>
<td>54.84</td>
</tr>
<tr>
<td>Life time (year)</td>
<td>5</td>
<td>57.84</td>
<td>6.228</td>
<td>9.228</td>
<td>57.84</td>
</tr>
<tr>
<td>Solar radiation (W/m&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>1040</td>
<td>57.62</td>
<td>1200</td>
<td>1200</td>
<td>57.84</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>37.01</td>
<td>57.81</td>
<td>49.01</td>
<td>50</td>
<td>57.84</td>
</tr>
<tr>
<td>Fuel cell operating temperature (C)</td>
<td>63.84</td>
<td>56.91</td>
<td>85.84</td>
<td>100</td>
<td>55.88</td>
</tr>
</tbody>
</table>

The single objective optimization results for the total cost rate of system 1 are demonstrated in Table 5.2. Furthermore, the results sensitivity are included, and it is carried out by altering the decision variable by 20%. The best total cost rate of the system is found to be
$9.432$/h. The PV area and solar radiation are found to be closer to the lower bound because reducing the PV area will mitigate the PV cost and will reduce overall system cost. Fuel cell current density is also found to be close to the maximum bound since running fuel cell with high current density would require a smaller number of cells and consequently lower fuel cell stack cost. The results of the single optimization and multi-objective optimization for system 1 are presented in Table 5.3

Table 5.2 Single objective optimization results for the total cost rate of system 1 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area(_{FC}) (cm(^2))</td>
<td>840</td>
<td>9.431</td>
<td>900</td>
<td>900</td>
<td>9.3</td>
</tr>
<tr>
<td>Area(_{PV}) (m(^2))</td>
<td>2</td>
<td>9.431</td>
<td>2</td>
<td>2.3</td>
<td>9.886</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>9.432</td>
<td>0.02</td>
<td>0.046</td>
<td>11.32</td>
</tr>
<tr>
<td>Current density (mA/cm(^2))</td>
<td>1249</td>
<td>9.405</td>
<td>1489</td>
<td>1500</td>
<td>9.05</td>
</tr>
<tr>
<td>Life time (year)</td>
<td>15.38</td>
<td>10.67</td>
<td>18.38</td>
<td>20</td>
<td>8.92</td>
</tr>
<tr>
<td>Solar radiation (W/m(^2))</td>
<td>400</td>
<td>9.356</td>
<td>410</td>
<td>570.2</td>
<td>10.61</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>-10</td>
<td>9.429</td>
<td>-8</td>
<td>4</td>
<td>9.542</td>
</tr>
<tr>
<td>Fuel cell operating temperature (C)</td>
<td>57.24</td>
<td>9.637</td>
<td>79.24</td>
<td>100</td>
<td>13.27</td>
</tr>
</tbody>
</table>

Table 5.3 Comparison of optimized parameters and base case using single and multi-objective optimization

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>Base case</th>
<th>Best exergy efficiency</th>
<th>Best total cost rate ($/h)</th>
<th>Multi-objective best efficiency and best total cost rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area(_{FC}) (cm(^2))</td>
<td>900</td>
<td>300</td>
<td>900</td>
<td>845.5</td>
</tr>
<tr>
<td>Area(_{PV}) (m(^2))</td>
<td>3</td>
<td>3.484</td>
<td>2</td>
<td>2.825</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.07</td>
<td>0.02123</td>
<td>0.02</td>
<td>0.02422</td>
</tr>
<tr>
<td>Current density (mA/cm(^2))</td>
<td>1150</td>
<td>400.8</td>
<td>1489</td>
<td>1493</td>
</tr>
<tr>
<td>Life time (year)</td>
<td>10</td>
<td>6.228</td>
<td>18.38</td>
<td>20</td>
</tr>
<tr>
<td>Solar radiation (W/m(^2))</td>
<td>1000</td>
<td>1200</td>
<td>410</td>
<td>981</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>25</td>
<td>49.01</td>
<td>-8</td>
<td>14.37</td>
</tr>
<tr>
<td>Fuel cell operating temperature (C)</td>
<td>70</td>
<td>85.84</td>
<td>79.24</td>
<td>68.88</td>
</tr>
</tbody>
</table>
5.2 System 2 Results and Comparison with System 1

A full parametric study is carried out on system 2 to evaluate the performance of the system with the variation of different system operating conditions. For instance, Fuel cell current density, AEC current density, Fuel cell and AEC operating temperature and solar radiation. Moreover, the effect of altering the reference temperature is investigated. Furthermore, the potential of adding photovoltaic panel to systems 1 and 2 is investigated and compared to determine which system is more efficient to generate/save hydrogen on board.

Fig. 5.14 shows the relationship between fuel cell current density and the overall energy and exergy efficiencies of system 1 and system 2. Energy and exergy efficiencies of system 1 show a decline from 60.95 to 37.7% and from 61.66 to 38.4% respectively when increasing the current density from 100 to 1600 mA/cm$^2$. Moreover, for the same range of the fuel cell current density, system 2 energy and exergy efficiencies display a deterioration from 67.48 to 39.17% and from 64.34 to 39.12% respectively. Increasing the current density would directly cause a growth in the fuel cell losses, and eventually, the fuel cell voltage will be reduced leading to a mitigation in the efficiency of the system. Moreover, the power output of the fuel cell is observed to be increasing from 11.53 to 110.6 kW when the fuel cell current density increased from 100 to 1424 mA/cm$^2$.

Fig. 5.15 demonstrates the effect of altering the AEC current density on the AEC electrolysis voltage, energy and exergy efficiencies of the AEC unit. The electrolysis voltage required to separate the ammonia increased from 0.1448 V to 0.172 V due to the increase in the AEC current density from 50 to 1000 mA/cm$^2$. However, changing AEC current density leads to a drop in the energy and exergy efficiency of the AEC unit from 81.35 to 79.25% and from 81.3 to 77.95% respectively. The energy efficiency of the AEC unit is found to be 82.34%, which in agreements with the AEC energy efficiency results reported by Gwak et al. [59]. The increase in the electrolysis voltage and the decrease in the energy and exergy efficiency of the AEC unit can be interpreted by the growth in the AEC voltage losses. Therefore, the electrolysis voltage increases in a directly proportional trend with the increase in the current density leading to an increase in the exergy destruction rate and eventually a decline in the AEC efficiency.
Fig. 5.14 Effect of changing fuel cell current density on overall energy and exergy efficiencies for systems 1 and 2.

Fig. 5.15 Effect of changing AEC current density on electrolysis voltage and overall energy and exergy efficiencies of the AEC.
The increase in exergy destruction rate due to the growth in the AEC current density is shown in Fig.5.16. Moreover, Fig.5.16 displays the increase in the AEC current density from 50 to 500 mA/cm², which leads to an upsurge in the hydrogen produced by the electrolysis process from 1 to 10.4 g/min. Fig.5.17 depicts the effect of varying the fuel cell operating temperature on the overall energy and exergy efficiencies of system 1 and system 2. Increasing the fuel cell operating temperature from -10 to 80 °C increases the energy and exergy efficiencies of system1 from 26.95 to 45.6% and from 26.96 to 45.13% respectively. Furthermore, for the same range of the fuel cell operating temperature, an increase in the energy and exergy efficiencies of system 2 are observed. The overall energy and exergy efficiencies show an upsurge from 29.52 to 47.2% and from 28.99 to 47.21% respectively. This behavior can be justified by the fact that increasing the operating cell temperature was a reason for the reduction in the fuel cell voltage losses resulting in a better fuel cell performance. Fig.5.18 shows the effects of increasing the ambient temperature on energy and exergy efficiencies of systems 1 and 2, and energy and exergy efficiencies of the AEC unit. The energy efficiencies of systems 1 and 2, and AEC show a constant energy efficiency value since changing the ambient temperature does not interfere with any of
energy efficiency calculations. Furthermore, changing the ambient temperature shows insignificant variation in the exergy efficiencies of systems 1 and 2 and AEC unit, although the variation is not significant it leads to an increase in the exergy efficiency of system 1 and a lessening in the exergy efficiency of system 2 and AEC unit.

Fig.5.19 shows the effect of increasing solar radiation on AEC exergy destruction and the overall energy and exergy efficiencies of systems 1 and 2. Augmenting solar radiation from 600 to 1200 W/m² leads to an increase in the overall energy and exergy efficiencies of system 1 from 45.86 to 46.01% and from 46.26 to 46.43% respectively. Furthermore, energy and exergy efficiencies of system 2 show an increase from 46.84 to 47.9% and from 46.93 to 47.69% respectively. Energy and exergy efficiencies of system 2 are influenced with the variation in the solar radiation more than system1. Increasing the solar insolation will increase the PV output power, which will provide the AEC unit with an extra electrolysis power. More electrolysis power results in an increase in the hydrogen generation from the AEC unit and consequently an increase in the exergy destruction rate of the AEC unit.

Fig. 5.17 Effect of changing fuel cell operating temperature on the overall energy and exergy efficiencies of systems 1 and 2.
Fig. 5.18 Effect of changing reference temperature on the overall energy and exergy efficiencies for systems 1, 2 and AEC unit.

Fig. 5.19 Effect of changing solar radiation on the overall energy and exergy efficiencies of systems 1 and 2 and the exergy destruction of AEC.
Fig. 5.20 demonstrates the effect of altering solar radiation on the amount of hydrogen that can be saved from system 1 or generated by system 2. Increasing solar radiation from 100 to 1000 W/m² will increase the amount of hydrogen that could be saved in system 1 from 0.33 to 2.963 g/min respectively. Also, varying solar radiation from 100 to 1000 W/m² will increase the amount of hydrogen generated from AEC in system 2 to from 0.52 to 5.23 g/min, which reveals that system 2 is more efficient regarding producing/saving hydrogen compared to system 1.

Fig. 5.20 Effect of changing solar radiation on hydrogen production from AEC in system 2 and the amount of hydrogen that could be saved in system 1.

Fig.5.21 shows the effect of changing the mass of ammonia entering AEC unit on the amount of hydrogen produced from the AEC, energy and exergy efficiencies of the AEC and system 2 at constant output energy of 16 kW from PV. Varying the mass of ammonia from 0.35 to 29.3 g/min causes the energy and exergy efficiencies of AEC to increase from 6 to 80% and from 5.5 to 78.6% respectively. However, the overall energy and exergy efficiencies of system 2 show a declination from 38 to 35.6% and from 54.2 to 50% respectively. Fig.22 shows the effect of increasing the interest rate for the purchased cost of the equipment of system 2 on the exergoeconomic factor and total cost rate. Increasing the interest rate from 2 to 15% increases the exergoeconomic factor from 29.33 to 38.06%
while the same range of interest rate variation results in an increase in the total cost rate from 58 to 79.8 $/h. However, increasing system 2 operational life from 5 years to 20 years leads to a mitigation in both, the exergoeconomic factor, and total cost rate from 40.88 to 26.83% and from 90.97 to 53.73 $/h respectively as shown in Fig.5.23.

Fig. 5.21 Effect of changing ammonia mass flow rate entering AEC on the overall energy and exergy efficiencies of system 2, AEC, and the hydrogen produced by AEC.

Fig. 5.22 Effect of varying the interest rate on the exergoeconomic factor and total cost rate of system 2.
Table 5.4 shows the single objective optimization for the exergy efficiency of system 2; the table also incorporates the results sensitivity. The decision variables include the area of the fuel cell, the area of PV and area of AEC. Fuel cell and AEC current density along with AEC and fuel cell operating temperature and ambient temperature are also chosen as decision parameters. For the PV part, the area of the PV and solar insolation are both considered as essential decision parameters. Table 5.5 shows the single objective optimization for the total cost rate of system 2 and Table 5.6 shows the best values from the single objective optimization for exergy efficiency, total cost rate and the results of the multi-objective optimization. The decision parameters that are similar to the first system shows almost the same results that obtained by system1 during the optimization study. However, the decision variables of the AEC unit such as its current density and the area of the AEC cell showed values close to the lower bounds in the single optimization of the exergy efficiency and values close to the higher bounds when total cost rate is targeted to be minimized during the single optimization study.
Table 5.4 Single objective optimization results for the exergy efficiency of system 2 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area_{FC} (cm²)</td>
<td>300</td>
<td>62.03</td>
<td>307.6</td>
<td>487.6</td>
<td>60.38</td>
</tr>
<tr>
<td>Area_{elec} (cm²)</td>
<td>724</td>
<td>61.94</td>
<td>784</td>
<td>844</td>
<td>61.94</td>
</tr>
<tr>
<td>Area_{PV} (m²)</td>
<td>3.174</td>
<td>57.7</td>
<td>3.474</td>
<td>3.5</td>
<td>61.97</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>11.25</td>
<td>61.94</td>
<td>0.1385</td>
<td>0.15</td>
<td>61.94</td>
</tr>
<tr>
<td>Fuel cell Current density (mA/cm²)</td>
<td>400</td>
<td>62.13</td>
<td>411.6</td>
<td>631.6</td>
<td>58.75</td>
</tr>
<tr>
<td>AEC Current density (mA/cm²)</td>
<td>250</td>
<td>61.98</td>
<td>265.9</td>
<td>335.9</td>
<td>61.78</td>
</tr>
<tr>
<td>Life time (year)</td>
<td>14.9</td>
<td>61.94</td>
<td>17.9</td>
<td>20</td>
<td>61.94</td>
</tr>
<tr>
<td>Solar radiation (W/m²)</td>
<td>1066</td>
<td>61.56</td>
<td>1186</td>
<td>1200</td>
<td>61.98</td>
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<tr>
<td>Ambient temperature (°C)</td>
<td>12.15</td>
<td>62.03</td>
<td>20.15</td>
<td>28.15</td>
<td>61.85</td>
</tr>
<tr>
<td>Fuel cell operating temperature (°C)</td>
<td>69.35</td>
<td>61.5</td>
<td>91.35</td>
<td>100</td>
<td>60.63</td>
</tr>
<tr>
<td>AEC operating temperature (°C)</td>
<td>-10</td>
<td>62.09</td>
<td>-3.22</td>
<td>8.774</td>
<td>61.69</td>
</tr>
</tbody>
</table>

Table 5.5 Single objective optimization results for the total cost rate of system 2 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area_{FC} (cm²)</td>
<td>730</td>
<td>8.206</td>
<td>878.2</td>
<td>888.7</td>
<td>8.056</td>
</tr>
<tr>
<td>Area_{elec} (cm²)</td>
<td>641.8</td>
<td>8.21</td>
<td>701.8</td>
<td>761.8</td>
<td>8.21</td>
</tr>
<tr>
<td>Area_{PV} (m²)</td>
<td>2.53</td>
<td>8.206</td>
<td>2.83</td>
<td>3.13</td>
<td>8.215</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>8.053</td>
<td>0.02265</td>
<td>0.04865</td>
<td>9.866</td>
</tr>
<tr>
<td>Fuel cell current density (mA/cm²)</td>
<td>1200</td>
<td>8.518</td>
<td>1470</td>
<td>1495</td>
<td>8.09</td>
</tr>
<tr>
<td>AEC Current density (mA/cm²)</td>
<td>436</td>
<td>8.209</td>
<td>506</td>
<td>576</td>
<td>8.221</td>
</tr>
<tr>
<td>Life time (year)</td>
<td>16.94</td>
<td>9.094</td>
<td>19.94</td>
<td>20</td>
<td>8.196</td>
</tr>
<tr>
<td>Solar radiation (W/m²)</td>
<td>600</td>
<td>8.206</td>
<td>666</td>
<td>786</td>
<td>8.218</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>18.92</td>
<td>8.182</td>
<td>26.92</td>
<td>34.92</td>
<td>8.234</td>
</tr>
<tr>
<td>Fuel cell operating temperature (°C)</td>
<td>49.03</td>
<td>8.483</td>
<td>71.03</td>
<td>93.03</td>
<td>9.463</td>
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<tr>
<td>AEC operating temperature (°C)</td>
<td>3.978</td>
<td>8.205</td>
<td>15.98</td>
<td>27.98</td>
<td>8.214</td>
</tr>
</tbody>
</table>
5.3 System 3 Results.

A parametric study is performed on system 3 to assess its performance with changing operating conditions. For instance, changing the ammonia and hydrogen molar flow rate entering the ICE, varying the mass flow rate of ammonia entering the DSU and the amount of heat supplied to the DSU. Fig.5.24 shows the influence of changing the molar flow rate of ammonia supplied to ICE on the power obtained from the ICE, torque of the ICE, and exergy destruction rate of the ICE. Changing ammonia molar flow rate from 7 to 70 mol/min increases the ICE output power from 18.6 to 117.9 kW. The same variation of molar variation resulted in an upsurge in the ICE exergy destruction rate from 28.8 to 194.8 kW. Moreover, engine torque increased from 194 N.m at 7 mol/min of ammonia supply into the ICE to reach a maximum value of 216.8 N.m at an ammonia fuel supply of 42.12 mol/min. After that, the torque started to decrease until it reaches a value of 176.1 at an ammonia flow rate of 70 mol/min.
Fig. 5.25 demonstrates the influence of changing the molar flow rate of ammonia entering the ICE on the overall exergy destruction rate of system 3, the exergy that could be recovered due to the utilization of the DSU, and the overall energy and exergy efficiencies of system 3. Increasing the molar flow rate of ammonia supplied to the ICE from 7 to 70 mol/min with a constant amount of hydrogen supply leads to a reduction in the overall energy and exergy efficiencies of system 3 from 74.6% to 36.7% and from 69.5% to 34.37% respectively. The reduction in the exergy efficiency can be interpreted by the increase in the exergy destruction rate from 2.3 kW to 168 kW as shown in Fig. 5.25. However, the increase in the ammonia flow rate will result in an increase in the amount of the exhaust gases that can be released from the system and consequently an upsurge in the amount of heat that can be supplied to the DSU will be achieved leading to an extra hydrogen production and additional recovered exergy.

Fig.5.26 shows the effect of changing the molar flow rate of ammonia entering the ICE on the amount of hydrogen and nitrogen that can be released from the DSU and the maximum amount of hydrogen that can be generated by the DSU. Increasing ammonia molar flow rate from 7 to 70 mol/min increases the amount of the hydrogen required for a better
ammonia combustion and nitrogen that can be released from the DSU from 0.625 to 6.246 mol/min and from 0.2 to 2 mol/min respectively. However, due to the higher mass flow rate of the exhaust gases leaving the ICE, additional hydrogen can be generated via the DSU. The maximum amount of hydrogen that can be generated with the increase of the ammonia molar flow rate from 7 to 70 mol/min can vary from 7.48 to 74 mol/min.

![Graph](image_url)

Fig. 5.25 Effect of changing amount of ammonia entering ICE, $\dot{N}_4$ on the overall energy and exergy efficiencies of system 3, exergy destruction rate of the whole system and the exergy recovered due to DSU installation.

Fig. 5.27 displays the influence of changing the amount of hydrogen supplied to the ICE from DSU on the overall energy and exergy efficiencies of the system and its exergy destruction rate, ICE output power and the exergy that can be recovered from the DSU. Increasing the amount of hydrogen flow rate from 0.6 to 6.2 mol/min can lead to an enhancement in the ICE energy and exergy efficiencies from 30.7 to 36.72% and from 28.8 to 34.37% respectively. The exergy destruction rate of the system is also increased from 185.5 to 194.8 kW. This increase in the hydrogen supply means that the DSU is generating extra hydrogen and consequently more exergy is recovered. For the same range of variation of the supplied hydrogen, the exergy recovered can be increased from 2.665 to 26.4 kW.
Fig. 5.26 Effect of changing amount of ammonia entering ICE, $\dot{N}_4$ on the produced hydrogen and nitrogen from the DSU unit and on the potential amount of hydrogen that can be provided by the DSU.

Fig. 5.27 Effect of varying amount of hydrogen supplied to the ICE on the exergy destruction rate of the system, ICE power, exergy that can be recovered and system overall energy and exergy efficiencies.
Fig. 5.28 depicts the effect of increasing the amount of heat supplied to the DSU on the potential amount of hydrogen and nitrogen that can be released from the DSU and the amount of the exergy that can be recovered from the DSU. Augmenting the amount of the decomposition heat that is supplied to the DSU from 3.8 to 38 kW increases the amount of hydrogen and nitrogen that can be produced from the DSU from 7.48 to 74.8 mol/min and from 2.5 to 24.9 mol/min respectively. Moreover, the exergy recovered from the system increases from 4.4 to 43 kW. Fig. 5.29 shows the alteration in the amount of hydrogen that can be produced from the DSU with the change in the amount of ammonia entering the ICE at different DSU conversion efficiency. The amount of the hydrogen produced in the three cases is corresponding to the maximum amount of hydrogen that can be produced using the maximum available decomposition heat from the released exhaust gases. Increasing the molar flow rate of ammonia entering the ICE from 7 to 70 mol/min results in an increase in the amount of hydrogen produced from the DSU from 7.48 to 74.8 mol/min. Moreover, it is observed that the maximum hydrogen production from the DSU at conversion efficiencies of 80 and 60% are found to be varying from 5.9 to 59.8 mol/min and from 4.4 to 44.8 mol/min respectively when varying the ammonia molar flow rate entering the ICE from 7 to 70 mol/min. This figure also asserts that DSU is capable of providing the adequate amount of hydrogen that is required for proper ammonia combustion even at 60% DSU conversion efficiency.

For this system, a dynamic analysis is carried out using the world harmonized light vehicle test procedure (WLTP). This system along with system 5 are chosen to be simulated in the dynamic mode using the previously mentioned driving cycle. These systems are chosen to be modeled dynamically because they have the potential to replace the current conventional vehicle systems with minor manufacturing modifications to the current ICE design. Moreover, the parts that need to be added to the systems are not expensive. In overall, these systems can be easily commercialized in the near future. The WLTP driving cycle is shown in Fig. 5.30, it consists of 4 phases with a total duration of 1800 seconds, and the vehicle in these phases experiences transition modes such as; accelerations, decelerations and idling, this is mainly to evaluate vehicle performance in every possible driving condition. The first phase is called the low phase, and its duration is 589 second, the vehicle in this phase attains
a maximum speed of 56.5 km/h. The second phase is called the medium phase, and its duration is 433 seconds, and the vehicle attains a maximum speed of 76.6 km/h.

Fig. 5.28 Effect of varying heat supplied to the DSU on the amount of hydrogen and nitrogen that can be released from the system and the exergy that could be recovered from the system.

Fig. 5.29 Variation of hydrogen produced on board from DSU with ammonia entering ICE at different DSU conversion efficiencies.
The third phase called the high phase, and its duration is 455 seconds, and the vehicle reaches a maximum speed of 97.4 km/h as shown in the Fig.5.35. The final phase is called the extra high phase, and the duration of this phase is 323 seconds, and the vehicle attains a maximum speed of 131.3 km/h. Figs.5.31-5.34 show the ICE output power, torque, and DSU decomposition heat variation during the WLTP driving cycle. The four phases of the driving cycles are separated for better presentation. In the first phase, the ICE output power and torque attains a maximum value of 43.79 kW and 210.3 N.m respectively at 228 seconds. The maximum decomposition heat available for ammonia decomposition is found to be 14.21 kW at 228 seconds as shown in Fig 5.31. In addition, in the second phase, the ICE output power, torque, and decomposition heat attain maximum values of 43.88 kW, 210.3 N.m, and 14.24 kW respectively at 646 seconds as shown in Fig.5.32. In the third phase, the ICE output power, torque and the heat available for ammonia thermal cracking reach maximum values of 43.79 kW, 210.3 N.m, and 14.21 kW respectively at 1126 seconds as shown in Fig 5.34. Finally, in the fourth phase, the ICE output power, torque, and decomposition heat reach maximum values of 52.74 kW, 213.6 N.m, and 17.12 kW respectively at 1724 seconds as shown in Fig.5.33.
Fig. 5.31 Variation of engine power, engine torque, and decomposition heat during the first phase of the WLTP driving cycle.

Fig. 5.32 Variation of engine power, engine torque, and decomposition heat during the second phase of the WLTP driving cycle.
Fig. 5.33 Variation of engine power, engine torque, and decomposition heat during the third phase of the WLTP driving cycle.

Fig. 5.34 Variation of engine power, engine torque, and decomposition heat during the fourth phase of the WLTP driving cycle.
Figs. 5.35-5.38 display the alteration in the ammonia molar consumption rate by the ICE, ammonia molar consumption rate by DSU, hydrogen consumption/produced by ICE/DSU, nitrogen released from DSU and the maximum amount of hydrogen that can be produced from DSU through the different phases of the WLTP driving cycles. In the first phase, the highest amount of ammonia consumption rate by the ICE, highest amount of ammonia consumption rate by DSU, hydrogen consumption/produced by ICE/DSU, the maximum amount of nitrogen released from DSU and maximum molar flow rate of hydrogen that can be produced from the DSU are found to be 25.55, 1.497, 2.273, 0.75 and 27.2 mol/min respectively at 229 seconds as shown in Fig. 5.35. In the second phase, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by DSU, hydrogen consumption/produced by ICE/DSU and the maximum amount of nitrogen released from DSU and maximum amount of hydrogen that can be obtained from the DSU are found to be 26.12, 1.549, 2.324, 0.77 and 27.8 mol/min respectively at 647 seconds as shown in Fig. 5.36.
Fig. 5.36 Variation of ammonia supplied to ICE, ammonia supplied to DSU, hydrogen, nitrogen and maximum hydrogen production that can be released from DSU during the second phase of the WLTP driving cycle.

Fig. 5.37 Variation of ammonia supplied to ICE and ammonia supplied to DSU, hydrogen, nitrogen and maximum hydrogen production that can be released from DSU during the third phase of the WLTP driving cycle.
In the third phases, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by DSU, hydrogen consumption/produced by ICE/DSU, the maximum amount of nitrogen released from the DSU and the maximum amount of hydrogen produced by the DSU are found to 26, 1.5, 2.3, 0.77 and 27.74 mol/min respectively at 1127 seconds as shown in Fig 5.37. In the fourth phase, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by DSU, hydrogen consumption/produced by ICE/DSU and the maximum amount of nitrogen that can be released from the DSU are found to 31.4, 1.8, 2.78, 0.931 and 33.4 mol/min respectively at 1725 seconds as shown in Fig 5.38.

Figs.5.39-5.42 illustrate the change of the exergy destruction rate of the system, exergy recovered by the system, expected exergy destruction rate and maximum amount of exergy that can be recovered if the system produces and uses the maximum possible hydrogen generated from the DSU. The maximum exergy destruction and exergy recovered in the regular case, at which the hydrogen produced is sufficient to enhance ICE performance are found to be 60 and 9.4 kW respectively in the first phase. While, for the maximum possible hydrogen production case, exergy destruction and exergy recovered from the system are found to be 53 and 15.53 kW respectively at 229 seconds as shown in Fig.5.39. In the second phase, The maximum exergy destruction and exergy recovered in the regular case are found to be 62 and 9.8 kW respectively. While, for the maximum possible hydrogen production case, exergy destruction and exergy recovered from the system are found to be 56 and 16.44 kW respectively at 647 seconds as shown in Fig 5.40.

In the third phase, The maximum exergy destruction and exergy recovered in the regular case are found to be 62.5 and 9.8 kW respectively. While, for the maximum possible hydrogen production case, exergy destruction and exergy recovered from the system are found to be 56 and 16.4 kW respectively at 1127 second as shown in Fig 5.41. Finally, in the fourth phase, The maximum exergy destruction and exergy recovered in the regular case are found to be 75.2 and 11.82 kW respectively. While, for the maximum possible hydrogen production case, exergy destruction and exergy recovered from the system are found to be 67.3 and 19.71 kW respectively at 1724 second as shown in Fig.5.42.
Fig. 5.38 Variation of ammonia supplied to ICE and ammonia supplied to DSU, hydrogen, nitrogen and maximum hydrogen production that can be released from DSU during the fourth phase of the WLTP driving cycle.

Fig. 5.39 Variation of exergy destruction rate of the system and exergy recovered during the first phase of the WLTP driving cycle.
Fig. 5.40 Variation of exergy destruction rate of the system and exergy recovered during the second phase of the WLTP driving cycle.

Fig. 5.41 Variation of exergy destruction rate of the system and exergy recovered during the third phase of the WLTP driving cycle.
Fig. 5.42 Variation of exergy destruction rate of the system and exergy recovered during the fourth phase of the WLTP driving cycle.

Fig. 43 shows the power and torque map characteristics of system 3. It is observed from the figure that the power keeps increasing until it reaches the maximum value of 118 kW at 6500 rpm, and beyond this engine speed, the power curve of the vehicle starts to deteriorate. Furthermore, the engine torque increased until it reaches a maximum value of 316.5 N.m at an engine speed of 3200 and it starts to decline after this engine speed until it reaches 142.7 N.m at 7500 rpm. Fig. 44 shows the effect of varying the interest rate on the exergoeconomic factor and total cost rate of system 3. Increasing the interest rate is observed to have a negative impact on the exergoeconomic factor and the total cost rate of the system since increasing the interest rate from 2 to 15% leads to an increase in the exergoeconomic factor and total cost rate of system 3 from 38.36 to 48.56% and from 12.51 and 17.7 $/h respectively. Fig. 45 shows the effect of varying the expected system operational lifetime on the exergoeconomic factor and total cost rate of the system. The total cost rate of the system reduces from 20.32 to 11.51 $/h when the system lifetime increased from 5 to 20 years. Moreover, the exergoeconomic factor of system 3 decreases from 51.75 to 35.34% when increasing the system lifetime from 5 to 20 years.
Fig. 5.43 Variation of the ICE output power and torque with engine speed for system 3.

Fig. 5.44 Effect of varying interest rate on the exergoeconomic factor and total cost rate of system 3.
Table 5.7 shows the single objective optimization results in the case of maximizing the exergy efficiency for system 3. The decision variables that are considered here are the amount of ammonia entering the ICE, hydrogen produced from the DSU to enhance the system efficiency, ambient temperature along with the interest rate and system operational life. The maximum obtainable exergy efficiency is found to be 66.86%.

Table 5.7 Single objective optimization results for exergy efficiency of system 3 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ flow rate (mol/min)</td>
<td>24</td>
<td>66.86</td>
<td>24</td>
<td>62.4</td>
<td>0.47</td>
</tr>
<tr>
<td>H₂ generated on board (mol/min)</td>
<td>44</td>
<td>62.07</td>
<td>54</td>
<td>54</td>
<td>0.66</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>32.86</td>
<td>66.86</td>
<td>44.86</td>
<td>50</td>
<td>66.86</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.12</td>
<td>66.86</td>
<td>0.1221</td>
<td>0.1461</td>
<td>66.86</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>5</td>
<td>66.86</td>
<td>5</td>
<td>8</td>
<td>66.86</td>
</tr>
</tbody>
</table>
Table 5.8 displays the single objective optimization results in case of minimizing the total cost rate of system 3. The lowest cost rate is found to be 1.44$/h. Table 5.9 depicts a comparison between best values for the decision variables in case of maximizing only the exergy efficiency, minimizing only the total cost rate, base values that are used in system modeling and optimum values achieved by the multi-objective optimization.

Table 5.8 Single objective optimization results for the total cost rate of system 3 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ flow rate (mol/min)</td>
<td>24</td>
<td>1.444</td>
<td>24</td>
<td>62.4</td>
<td>2.882</td>
</tr>
<tr>
<td>H₂ generated on board (mol/min)</td>
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<td>1.407</td>
<td>10.85</td>
<td>20.454</td>
<td>1.516</td>
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<tr>
<td>Ambient temperature (°C)</td>
<td>20.82</td>
<td>1.437</td>
<td>32.82</td>
<td>44.82</td>
<td>1.45</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>1.444</td>
<td>0.020</td>
<td>0.0461</td>
<td>1.645</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>15.17</td>
<td>1.579</td>
<td>18.17</td>
<td>20</td>
<td>1.381</td>
</tr>
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</table>

Table 5.9 Comparison of optimized parameters and base case using single and multi-objective optimization for system 3.

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>Base case</th>
<th>Best exergy efficiency</th>
<th>Best total cost rate ($/h)</th>
<th>Multi-objective best efficiency and best total cost rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ flow rate (mol/min)</td>
<td>70</td>
<td>24</td>
<td>24</td>
<td>24</td>
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<tr>
<td>H₂ generated on board (mol/min)</td>
<td>6.246</td>
<td>54</td>
<td>10.854</td>
<td>52.212</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>25</td>
<td>44.86</td>
<td>32.82</td>
<td>10</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.07</td>
<td>0.1221</td>
<td>0.02001</td>
<td>0.02004</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>10</td>
<td>5</td>
<td>18.17</td>
<td>19.97</td>
</tr>
</tbody>
</table>

5.4 System 4 Results.
This section includes the results of the parametric study that is carried out for system 4, the results of the exergoeconomic analysis and the optimization study are also incorporated. Fig.5.46 shows the variation of the power output of the fuel cell and ICE with the amount
of ammonia supplied to the internal combustion engine. As can be observed from the figure, the power output of the ICE increases from 15.5 to 119.2 kW and the fuel cell work output increases from 10.4 to 99.6 kW as the ammonia supplied to ICE increases from 7.3 to 73.3 mol/min. In addition, the energy and exergy efficiencies decrease from 52.7% and 49.3% to 36.9% and 34.6% respectively as the ammonia supplied to the ICE increases from 7.3 to 73.3 mol/min. The reduction in the exergy efficiencies can be interpreted by the increase in the exergy destruction rate of the fuel cell and ICE as shown in Fig. 5.47, which displays the variation of the exergy destruction rates of the fuel cell, ICE and overall system with the amount of ammonia supplied to the ICE. The exergy destruction rates in the fuel cell, ICE, and the overall system increase from 13.4 kW, 24.7 kW and 27.1 kW at an ammonia flow rate of 7.3 mol/min to 128.3 kW, 198.1 kW, and 344.3 kW at an ammonia flow rate of 73.3 mol/min. Fig. 5.48 shows the variation of the exergy recovered with the amount of heat supplied to the DSU. The exergy recovered increases from 8.7 kW to 87.5 kW as the heat supplied to DSU increases from 2.8 kW to 27.9 kW. Further, the hydrogen released from the DSU and supplied to the ICE increase from 0.4377 mol/min to 4.34 mol/min and the hydrogen released from the DSU and supplied to the fuel cell witnesses an upsurge from 5 mol/min and 50 mol/min when the heat supplied to the DSU increases from 2.8 kW to 27.9 kW. Installing a nitrogen turbine to this system can recover any waste energy leaving out of the system with the release of the nitrogen from the DSU. Fig. 4.49 shows the variation of obtained power from nitrogen expander and molar flow rate of nitrogen released from the system with the amount of heat supplied to the DSU. The power obtained from the expander increases from 0.38 to 3.8 kW as the heat supplied to DSU increases from 2.8 to 27.9 kW. Further, the nitrogen released from the DSU \( \dot{N}_7 \) increases from 1.8 to 18.1 mol/min as the heat supplied to the DSU increases from 2.8 to 27.9 kW. Fig. 5.50 shows the variation of the power outputs of the fuel cell and internal combustion engine as well as the exergy destruction rates with the amount of heat supplied to the DSU. As can be observed from the figure, the power outputs of the ICE and the fuel cell increase from 8.6 kW and 7 kW to 85.6 kW and 70 kW respectively as the amount of heat supplied to the DSU increases from 2.8 kW to 27.9 kW. Moreover, the exergy destruction rates in the fuel cell and the ICE increase from 9.0 kW and 14.2 kW to 90.2 and 142 kW respectively as the amount of heat supplied to the DSU increases from 2.8 kW to 27.9 kW.
Fig. 5.46 Variation of energy and exergy efficiency, work output of the ICE and work output of fuel cell with the amount of ammonia supplied to the ICE.

At $\dot{N}_9 = 3.314$ [mol/min]

Fig. 5.47 Variation of the exergy destruction rates with the amount of ammonia supplied to the ICE.

At $\dot{N}_9 = 3.314$ [mol/min]
Fig. 5.48 Variation of the exergy recovered and the amount of hydrogen released and supplied to ICE $\dot{N}_9$ and hydrogen released and supplied to the fuel cell $\dot{N}_{10}$ with the heat supplied to DSU.

Fig. 5.49 Variation of the power obtained from nitrogen expander and molar flow rate of nitrogen released from the DSU with the heat supplied to DSU.
Fig. 5.50 Variation of power output of ICE and fuel cell and the exergy destruction rates with the amount of heat supplied to DSU.

Fig. 5.51 Variation of the fuel cell and system exergy efficiencies and the exergy destruction rates with the ambient temperature.
Fig. 5.51 shows the variation of the system and fuel cell exergy efficiencies and the exergy destruction rates in the fuel cell, ICE, and system with the ambient temperature. As can be observed from the figure, the system exergy efficiency increases slightly from 35.3 to 35.5% as the ambient temperature is increased from 0 °C to 50 °C. In addition, the exergy destruction rates in the fuel cell, ICE and the system increase from 56.5 kW, 100.1 kW and 162.8 kW to 80.9 kW, 114.9 kW, and 200.3 kW respectively as the ambient temperature is increased from 0 to 50 °C.

![Graph showing the variation of exergy efficiencies and destruction rates](image)

**Fig. 5.52** Variation of the fuel cell and system energy and exergy efficiencies and the exergy destruction rates with the fuel cell operating temperature.

Fig. 5.52 shows the variation of the system and fuel cell energy and exergy efficiencies and the exergy destruction rates in the fuel cell and the system with the fuel cell operating temperature. The fuel cell energy and exergy efficiencies increase from 27.3% and 27.6% to 43.4% and 43.9% respectively as the fuel cell operating temperature increases from 0 to 90 °C. Furthermore, the system energy and exergy efficiencies increase from 33.3% and 31.3% to 39.3% and 36.8% respectively for the same temperature increase. Moreover, the exergy destruction rates in the fuel cell and the system decrease from 101.8 kW and 197 kW to 68.3 kW and 176.5 kW respectively as the operating temperature of the fuel cell increases from 0 to 90 °C. This behavior can be interpreted by the fact that increasing the
fuel cell operating temperature mitigate the losses inside the fuel cell which directly enhance the fuel cell system performance and consequently the overall system performance. Figure 5.53 shows the variation of the system and fuel cell energy and exergy efficiencies and the exergy destruction rates in the fuel cell and the system with the fuel cell current density. The fuel cell energy and exergy efficiencies decrease from 51.0 and 51.6% to 36.7 to 37.2% respectively as the current density increases from 400 to 1500 mA/cm². Furthermore, the system energy and exergy efficiencies decrease from 42.1 and 39.43% to 36.9 and 34.5% respectively for the same temperature increase. Moreover, the exergy destruction rates in the fuel cell and the system increase from 57.9 kW and 166.8 kW to 73.8 kW and 185 kW respectively as the current density increases from 400 to 1500 mA/cm². It is noted that increasing the fuel cell current density has a negative impact on fuel energy and exergy efficiencies due to the increase in the losses inside the fuel cell, reduction in the performance of the fuel cell will lead to a deterioration in the overall energy and exergy efficiencies.

Fig. 5.53 Variation of the fuel cell and system energy and exergy efficiencies and the exergy destruction rates with the fuel cell current density.

Fig. 5.54 shows different exergy destruction rates for the major contributing components in system 3 and 4 at a maximum obtained power of 118 kW. Exergy destruction rate of the
ICE in system 3 is found to be as 194.8 kW, while in system 4 it is recorded as 107.9. The exergy destruction rate of the fuel cell is found to be 62.5 kW. System 3 was able to recover 26.5 kW of waste energy from the exhaust gases. Nevertheless, system 4 was able to recover more exergy by using the waste power from the exhaust gases to run a fuel cell with an output power of 52 kW. Furthermore, the total exergy destruction of system 3 and system 4 are found to be 168.3 kW and 178.7 kW respectively.

Fig. 5.54 Exergy destruction rates for a fuel cell, ICE, ICE+DSU in system 3 and 4, and the maximum exergy recovered by each system.

Fig. 5.55 displays the variation of the amount of hydrogen produced from DSU and supplied to the fuel cell and fuel cell power output with the change in the ammonia molar flow rate entering the ICE at different DSU conversion efficiencies. Increasing the amount of ammonia entering the ICE from 3.66 to 36.6 mol/min results in an upsurge in the amount of hydrogen produced from DSU and supplied to the fuel cell from 3.86 to 35.7 mol/min and from 3 to 28.6 mol/min and from 2.31 to 21.45 at 100%, 80% and 60% conversion efficiencies respectively. Moreover, augmenting the amount of ammonia entering the ICE from 3.66 to 36.6 mol/min leads to an increase in the fuel cell output power from 5.4 to 50 kW at 100% DSU conversion efficiency and from 4.3 to 40 kW at 80% conversion efficiency and from 3.2 to 30 kW at 60% DSU conversion efficiency. It is observed from
the figure that the amount of hydrogen delivered to the fuel cell and consequently the fuel cell output power decrease with any mitigation in the DSU conversion efficiency. This is mainly due to the reduction in the amount of the ammonia that can potentially decompose during the thermal cracking process inside the DSU.

Fig. 55 shows the power and torque map characteristics of system 4. It is observed from the figure that the power kept increasing until it reaches the maximum value of 63 kW at 6500 rpm, and beyond this engine speed, the power curve of the vehicle starts to deteriorate until it reaches 59.9 kW of power at 7500 rpm. Furthermore, the engine torque increased until it reaches a maximum value of 115.6 N.m at an engine speed of 3200 and it starts to decline until it reaches 76.16 N.m at 7500 rpm.

Fig. 5.57 shows the effect of varying the interest rate on the exergoeconomic factor and total cost rate of system 4. Increasing the interest rate from 2 to 15% leads to an upsurge in the exergoeconomic factor from 22.77 to 30.91%. Furthermore, increasing the interest rate causes an increase in the total cost rate of the system from 34.9 to 45.6 $/h.
Fig. 5.56 Torque and power map characteristics for the ICE in system 4.

Fig. 5.57 Effect of varying interest rate on the exergoeconomic factor and total cost rate of system 4.
The effect of varying the expected lifetime of the system from 5 to 20 years is shown in Fig. 5.58. Any upsurge in the system lifetime results in a mitigation in the exergoeconomic factor from 33.7 to 20.57%. The same declination behavior is observed for the total cost rate of the system, at which the total cost rate is reduced from 51.9 to 32.46 $/h.

Table 5.10 shows the single optimization results for maximizing exergy efficiency of system 4. The decision parameters that are used in this study are current density, operating temperature and single cell area for the fuel cell stack. Interest rate and system life are also incorporated in the study along with the ambient temperature. Table 5.11 shows the optimized decision parameters that are obtained to achieve the lowest total cost rate values for system 4. It is noted from the table that the best total cost rate can be obtained by reducing the interest rate to the minimum and increasing system life to the maximum allowable value along with the increase in the fuel cell current density to reduce the required number of cells inside the fuel cell stack. Table 5.12 shows a comparison between the base values for the decision variable that are utilized in system modeling, the corresponding values in the case of best exergy efficiency, best values for the lowest total
cost rate and the best values that can achieve the best efficiency along with the best total cost rate.

Table 5.10 Single objective optimization results for exergy efficiency of system 4 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
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<tr>
<td>Area$_{fc}$ (cm$^2$)</td>
<td>675.3</td>
<td>60.9</td>
<td>795.3</td>
<td>915</td>
<td>60.9</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.0593</td>
<td>61</td>
<td>0.08533</td>
<td>0.1113</td>
<td>61</td>
</tr>
<tr>
<td>Fuel cell current density (mA/cm$^2$)</td>
<td>400</td>
<td>61.31</td>
<td>471</td>
<td>691</td>
<td>60.4</td>
</tr>
<tr>
<td>NH$_3$ flow rate (mol/min)</td>
<td>24</td>
<td>61.2</td>
<td>24</td>
<td>62.4</td>
<td>46.73</td>
</tr>
<tr>
<td>H$_2$ generated on board (mol/min)</td>
<td>46.38</td>
<td>57.37</td>
<td>53.58</td>
<td>55</td>
<td>61.22</td>
</tr>
<tr>
<td>System life time (year)</td>
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<td>13.45</td>
<td>16.45</td>
<td>61.08</td>
</tr>
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<td>60.7</td>
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<tr>
<td>Fuel cell operating temperature (C)</td>
<td>59.93</td>
<td>60.53</td>
<td>81.93</td>
<td>100</td>
<td>61.25</td>
</tr>
</tbody>
</table>

Table 5.11 Single objective optimization results for the total cost rate of system 4 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area$_{fc}$ (cm$^2$)</td>
<td>666.1</td>
<td>4.354</td>
<td>786.1</td>
<td>906.1</td>
<td>4.354</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>4.353</td>
<td>0.02005</td>
<td>0.04605</td>
<td>4.879</td>
</tr>
<tr>
<td>Fuel cell current density (mA/cm$^2$)</td>
<td>829</td>
<td>4.354</td>
<td>1430</td>
<td>1439</td>
<td>4.151</td>
</tr>
<tr>
<td>NH$_3$ flow rate (mol/min)</td>
<td>24</td>
<td>4.353</td>
<td>24</td>
<td>62.4</td>
<td>9.907</td>
</tr>
<tr>
<td>H$_2$ generated on board (mol/min)</td>
<td>7</td>
<td>4.167</td>
<td>16.6</td>
<td>26.19</td>
<td>4.542</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>15.82</td>
<td>4.68</td>
<td>18.82</td>
<td>20</td>
<td>4.253</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>10</td>
<td>4.16</td>
<td>10</td>
<td>19</td>
<td>4.633</td>
</tr>
<tr>
<td>Fuel cell operating temperature (C)</td>
<td>59.58</td>
<td>4.53</td>
<td>81.58</td>
<td>100</td>
<td>7.561</td>
</tr>
</tbody>
</table>
Table 5.12 Comparison of optimized parameters and base case using single and multi-objective optimization for system 4

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>Base case</th>
<th>Best exergy efficiency</th>
<th>Best total cost rate ($/h)</th>
<th>Multi-objective best efficiency (61.29%) and best total cost rate (7.775$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area&lt;sub&gt;FC&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>900</td>
<td>795.3</td>
<td>786.1</td>
<td></td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>6.246</td>
<td>0.08533</td>
<td>0.02005</td>
<td></td>
</tr>
<tr>
<td>Fuel cell current density (mA/cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>1150</td>
<td>471</td>
<td>1430</td>
<td></td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt; flow rate (mol/min)</td>
<td>70</td>
<td>24</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; generated on board (mol/min)</td>
<td>6.246</td>
<td>53.58</td>
<td>16.6</td>
<td></td>
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<tr>
<td>System life time (year)</td>
<td>10</td>
<td>13.45</td>
<td>18.82</td>
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<tr>
<td>Ambient temperature (C)</td>
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<td>18</td>
<td>10</td>
<td></td>
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<tr>
<td>Fuel cell operating temperature (C)</td>
<td>70</td>
<td>81.93</td>
<td>81.58</td>
<td></td>
</tr>
</tbody>
</table>

5.5 System 5 Results

A parametric study along with dynamic analysis utilizing the WLTP are carried out on system 5 for comprehensive performance evaluation. Results of the exergoeconomic analysis and optimization study are also included in this section. The analysis and assessment considered both, the first and second law of thermodynamics. Fig. 5.59 displays the effect of varying the ammonia molar flow rate entering the ICE on the ICE output power and output torque and exergy destruction rate of the ICE. Augmenting ammonia molar flow rate from 0.61 to 69.77 mol/min results in an upsurge in the ICE output power and exergy destruction rate from 1.1 to 117.2 kW and from 1.858 to 198.1 kW respectively. Furthermore, increasing ammonia molar flow rate entering the ICE from 0.61 to 41.88 mol/min rises the engine output torque from 175 to 216.8 N.m. However, increasing ammonia flow rate from 45.46 to 69.77 mol/min leads to a decrease in the engine output torque from 216.8 to 182.9 N.m. The trend of torque variation can be interpreted by the
fact that, increasing the amount of fuel entering the ICE is usually accompanied by an increase in the engine speed. This kind of behavior is common in any ICE Performance characteristic curves.

![Graph showing the effect of varying ammonia molar flow rate on ICE output power, ICE exergy destruction rate, and ICE output torque.](image)

**Fig. 5.59** Effect of varying the molar flow rate of ammonia entering the ICE on the ICE output power, ICE exergy destruction rate and ICE output torque of system 5.

Fig. 5.60 demonstrates the effect of varying ammonia molar flow rate entering the ICE on the TEG output power and exergy destruction rate of the TEG and AEC. Increasing ammonia molar flow rate from 10 to 69 mol/min leads to an increase in the TEG output power from 0.56 to 3.9 kW. Moreover, the same variation in ammonia molar flow rate results in an increase in the exergy destruction rate of the TEG and AEC from 3.4 to 23.49 kW and from 0.43 to 2.974 kW respectively. The marked upsurge in the TEG output power and exergy destruction is due to the increase of the exhaust molar flow rate leaving the ICE and entering the TEG system. Increasing the exhaust mass flow rate leads to additional exergy losses due to the increase in the non-utilized energy released with the exhaust. The upsurge in the electrolysis power (TEG output power) leads to an increase in the amount of the hydrogen produced from the AEC and consequently an augmentation in the exergy destruction rate of the AEC. It should be noted that the TEG maximum energy efficiency
is found to be 8% at maximum engine output power of 118 kW for a temperature difference of 240 °C between the hot and cold sides of the TEG system, which comes in accordance with the TEG energy efficiency results obtained by Barma et al. [64] for the same TEG material.

![Graph showing influence of changing the molar flow rate of ammonia entering the ICE on the TEG output power and Exergy destruction rate of TEG and AEC.](image)

Fig. 5.60 Influence of changing the molar flow rate of ammonia entering the ICE on the TEG output power (Electrolysis power), and Exergy destruction rate of TEG and AEC.

Fig. 5.61 depicts the effect of varying the ammonia molar flow rate entering the whole integrated system represented in the ICE and AEC unit on the overall energy and exergy efficiencies of the integrated system and its total exergy destruction rate. Increasing the molar flow rate of ammonia entering the integrated system from 6.5 to 124 mol/min results in a decrease in the overall energy and exergy efficiencies from 33.56 to 31 % and from 31.23 to 28.85% respectively. The reduction in the exergy efficiency is interpreted by the increase in the exergy destruction rate of the whole system as shown in Fig. 5.61, where the exergy destruction rate increased from 21.46 to 428.4 kW for the same range of variation of the ammonia molar flow rate. Moreover, the ICE output power increased from 11.26 to 196.2 kW with when the ammonia molar flow rate increased from 6.5 to 124 mol/min.

Figs. 5.62-5.65 show the ICE output power and torque and TEG output power variation.
during the WLTP driving cycle. In the first phase, the ICE output power and torque attain a maximum value of 43.79 kW and 210.3 N.m respectively at 229 seconds.

![Graph](image)

**Fig. 5.61** Effect of Varying Ammonia molar flow rate supplying the integrated system on the overall energetic and exergetic efficiencies and exergy destruction rate of the system.

The maximum TEG output power was found to be 1.482 kW at 229 seconds as shown in Fig 5.62. In addition, in the second phase, the ICE output power, torque and TEG output power attain maximum values of 43.8 kW, 210.2 N.m, and 1.47 kW respectively at 645 seconds as shown in Fig.5.63. In the third phase, the ICE output power, torque and TEG output power attain maximum values of 43.79 kW, 210.3 N.m, and 1.482 kW respectively at 1127 seconds as shown in Fig 5.64. Finally, in the fourth phase, the ICE output power, torque and TEG output power reach maximum values of 52.7 kW, 213.5 N.m and 1.784 kW respectively at 1724 seconds as shown in Fig.5.65.

Figs.5.66-5.69 display the alteration in the ammonia molar consumption rate by the ICE, ammonia molar consumption rate by AEC, hydrogen consumption/produced by ICE/AEC and the expected molar flow rate of the nitrogen and any NOx that could be released with the ICE exhaust gases through the different phases of the WLTP driving cycles. In the first phase, the highest amount of ammonia consumed by the ICE, maximum amount of
ammonia consumed by AEC, hydrogen consumption/produced by ICE/AEC and the maximum expected amount of molar flow rate of the nitrogen and NO\(_x\) released from ICE and AEC are found to be 26.06, 1.546, 2.319 and 90.93 mol/min respectively at 229 seconds as shown in Fig 5.66. Furthermore, in the second phase, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by AEC, hydrogen consumption/produced by ICE/AEC and the maximum amount of nitrogen and NO\(_x\) molar flow rate released from ICE and AEC are found to be 25.76, 1.528, 2.29 and 89.86 mol/min respectively at 645 seconds as shown in Fig.5.67. While, In the third phase, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by AEC, hydrogen consumption/produced by ICE/AEC and the maximum amount of the nitrogen and NO\(_x\) released from ICE and AEC are found to 26.06, 1.546, 2.319 and 90.93 mol/min respectively at 1127 seconds as shown in Fig 5.68. Finally, In the fourth phase, the highest amount of ammonia consumed by the ICE, maximum amount of ammonia consumed by AEC, hydrogen consumption/produced by ICE/AEC and the maximum amount of nitrogen and NO\(_x\) molar flow rate released from ICE and AEC are found to 31.36, 1.862, 2.793 and 109.5 mol/min respectively at 1724 second as shown in Fig 5.69.

Fig. 5.62 Variation of engine power, engine torque, and output power of the TEG unit during the first phase of the WLTP driving cycle.
Fig. 5.63 Variation of engine power, engine torque, and output power of the TEG unit during the second phase of the WLTP driving cycle.

Fig. 5.64 Variation of engine power, engine torque, and output power of the TEG unit during the third phase of the WLTP driving cycle.
Fig. 5.65 Variation of engine power, engine torque, and output power of the TEG unit during the fourth phase of the WLTP driving cycle.

Fig. 5.66 Variation of $NH_3$ consumption by the ICE and AEC, $H_2$ consumption by AEC and $N_2$ released from the system during the first phase of the driving cycle.
Fig. 5.67 Variation of $NH_3$ consumption by the ICE and AEC, $H_2$ consumption by AEC and $N_2$ released from the system during the second phase of the driving cycle.

Fig. 5.68 Variation of $NH_3$ consumption by the ICE and AEC, $H_2$ consumption by AEC and $N_2$ released from the system during the third phase of the driving cycle.
Fig. 5.69 Variation of $\text{NH}_3$ consumption by the ICE and AEC, $H_2$ consumption by AEC and $N_2$ released from the system during the fourth phase of the driving cycle.

Fig. 5.70 Variation of the exergy destruction rate of the ICE, TEG, and AEC during the first phase of the driving cycles.
Figures from (5.70-5.73) illustrate the change of the exergy destruction rate of the ICE, TEG, and AEC during the driving cycle test. For instance, in the first phase, the maximum destruction rate of the ICE, TEG, and AEC are found to be 73.98, 8.869 and 1.123 kW respectively at 229 seconds as shown in Fig.5.70. In the second phase, the highest destruction rate of the ICE, TEG, and AEC are found to be 73.11, 8.764 and 1.1 kW respectively at 645 seconds as shown in Fig.5.71. In the third phase, the highest destruction rate of the ICE, TEG, and AEC are found to be 73.98, 8.869 and 1.123 kW respectively at 1127 second as shown in Fig.5.72. Finally, in the fourth phase, the highest destruction rate of the ICE, TEG, and AEC are found to be 89.04, 10.67 and 1.35 kW respectively at 1724 second as shown in Fig.5.73. Fig.5.74 displays the variation of the total cost rate and the exergoeconomic factor of system 5 with the interest rate. Increasing the interest rate from 2 to 15% causes the system total cost rate to increase from 34.6 to 45.6 $/h. The same increase in the interest rate results in an increase in the exergoeconomic factor from 22.7 to 31%.
Fig. 5.72 Variation of the exergy destruction rate of the ICE, TEG, and AEC during the third phase of the driving cycles.

Fig. 5.73 Variation of the exergy destruction rate of the ICE, TEG, and AEC during the fourth phase of the driving cycles.
Fig. 5.74 Effect of varying interest rate on the exergoeconomic factor and total cost rate of system 5.

Fig. 5.75 Effect of varying system lifetime on the exergoeconomic factor and total cost rate of system 5.
The duration of the system lifetime has a critical influence on the system total cost rate. For system 5, increasing system operational lifetime from 5 to 20 years leads to a decrease in the exergoeconomic factor of system 5 from 33.7 to 20.57%. Moreover, the increase in the system lifetime results in a reduction in the total cost rate from 51.9 to 32.4 $/has shown in Fig.5.75.

Table 5.13 displays the optimized decision parameters for the best overall exergy efficiency for system 5. The decision variables that are included in the study are the area of the unit cell in the AEC unit and AEC current density and operating temperature. System lifetime and interest rate are also included along with the amount of ammonia entering the ICE and ambient temperature. Table 15.14 shows the optimized decision parameters for the lowest total cost rate for system 5. AEC cell area and current density are maximized to reduce the cost along with the interest rate. However, the system lifetime is increased to achieve the target of minimizing the total cost rate of the system. Table 5.18 shows the base values for the decision variables, the optimum values corresponding to the high exergy efficiency and highest total cost rate and finally the multi-objective optimization results.

Table 5.13 Single objective optimization results for exergy efficiency of system 5 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area_{elec} (cm$^2$)</td>
<td>433.2</td>
<td>30.12</td>
<td>553.2</td>
<td>673.2</td>
<td>30.12</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.0604</td>
<td>30.12</td>
<td>0.0864</td>
<td>0.1124</td>
<td>30.12</td>
</tr>
<tr>
<td>AEC current density (mA/cm$^2$)</td>
<td>288</td>
<td>30.12</td>
<td>368</td>
<td>448</td>
<td>30.12</td>
</tr>
<tr>
<td>NH$_3$ flow rate (mol/min)</td>
<td>24</td>
<td>30.12</td>
<td>24</td>
<td>62.4</td>
<td>29.42</td>
</tr>
<tr>
<td>H$_2$ generated on board (mol/min)</td>
<td>46.38</td>
<td>29.95</td>
<td>53.58</td>
<td>55</td>
<td>30.12</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>6.6</td>
<td>30.12</td>
<td>9.6</td>
<td>12.64</td>
<td>30.12</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>10</td>
<td>28.9</td>
<td>13</td>
<td>18</td>
<td>30.11</td>
</tr>
<tr>
<td>AEC operating temperature (C)</td>
<td>27.88</td>
<td>30.12</td>
<td>39.88</td>
<td>50</td>
<td>30.12</td>
</tr>
</tbody>
</table>
Table 5.14 Single objective optimization results for the total cost rate of system 5 including the sensitivities.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area&lt;sub&gt;elec&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>429.5</td>
<td>1.063</td>
<td>488</td>
<td>608</td>
<td>1.068</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>1.06</td>
<td>0.02211</td>
<td>0.04605</td>
<td>1.166</td>
</tr>
<tr>
<td>AEC current density (mA/cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>492</td>
<td>1.067</td>
<td>572</td>
<td>600</td>
<td>1.068</td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt; flow rate (mol/min)</td>
<td>24</td>
<td>1.067</td>
<td>24</td>
<td>62.4</td>
<td>2.56</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; generated on board (mol/min)</td>
<td>6</td>
<td>1.066</td>
<td>6.09</td>
<td>15.69</td>
<td>1.271</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>17</td>
<td>1.12</td>
<td>20</td>
<td>20</td>
<td>1.068</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>1.578</td>
<td>1.066</td>
<td>13.58</td>
<td>25.58</td>
<td>1.069</td>
</tr>
<tr>
<td>AEC operating temperature (C)</td>
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<td>1.067</td>
<td>18.88</td>
<td>30.88</td>
<td>1.069</td>
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</table>

Table 5.15 Comparison of optimized parameters and base case using single and multi-objective optimization for system 5

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>Base case</th>
<th>Best exergy efficiency</th>
<th>Best total cost rate ($/h)</th>
<th>Multi-objective best efficiency (29%) and best total cost rate (2$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area&lt;sub&gt;elec&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>600</td>
<td>553.2</td>
<td>488</td>
<td>704</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.07</td>
<td>0.0864</td>
<td>0.02211</td>
<td>0.02014</td>
</tr>
<tr>
<td>AEC current density (mA/cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>250</td>
<td>368</td>
<td>572</td>
<td>200</td>
</tr>
<tr>
<td>NH&lt;sub&gt;3&lt;/sub&gt; flow rate (mol/min)</td>
<td>70</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; generated on board (mol/min)</td>
<td>6.246</td>
<td>53.58</td>
<td>6.09</td>
<td>6</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>10</td>
<td>9.6</td>
<td>20</td>
<td>19.69</td>
</tr>
<tr>
<td>Ambient temperature (C)</td>
<td>25</td>
<td>13</td>
<td>13.58</td>
<td>10</td>
</tr>
<tr>
<td>AEC operating temperature (C)</td>
<td>20</td>
<td>39.88</td>
<td>18.88</td>
<td>13.6</td>
</tr>
</tbody>
</table>
5.6 System 6 Results

This section includes the results of the parametric study for system 6. The exergoeconomic analysis and optimization study results for system 6 are also included. Fig. 5.76 shows the effect of varying the mass flow rate of the natural gas supplied to the system on the overall energy and exergy efficiencies of the system and exergy destruction rate of the system. Increasing the mass flow rate of natural gas from 96 to 480 g/min results in an increase in the exergy destruction of the system from 61.64 kW to 329.4 kW, and an increase in the net power output from 16 to 80 kW. However, energy and exergy efficiencies of the overall system experienced mitigation from 51.43 to 30.77 % and from 52.84 to 28.9% respectively.

Fig. 5.76 Variation of exergy destruction rate and overall energy and exergy efficiencies of system 6 with the mass flow rate of natural gas supplied to the combustion chamber.

Fig. 5.77 shows the effect of varying the mass flow rate of the natural gas supplied to the system on the ORC, TEG, gas turbine output power and the available amount of cooling from ACC system. Increasing the natural gas mass flow rate from 96 to 480 g/min results in an increase in the ORC, TEG, and gas turbine output power from 2.9 to 10.9 kW, 1 to 5 kW and from 19.14 to 95 kW respectively. The output cooling from the ACC is also increased from 2 to 10 kW.
Fig. 5.77 Variation of ORC output power, TEG output power, gas turbine output power, and the obtained cooling effect with the mass flow rate of the natural gas supplied to the system.

Fig. 5.78 shows the influence of varying the mass flow rate of the natural gas on the exergy destruction rate of the ORC, combustion chamber, and the whole system. The exergy destruction rate of the ORC increased from 10.5 to 53 kW, while the exergy destruction rate of the combustion chamber and the gas turbine increased from 27.83 to 139.2 kW and from 0.9 to 4.5 kW respectively with the increase of natural gas mass flow rate from 96 to 480 g/min. Fig. 5.79 displays the effect of varying the compressor pressure ratio on the overall energy and exergy efficiencies of the system. The upsurge in the compression ratio from 2 to 10 results in an increase in the overall energy efficiency of the system from 26.58 to 35.18%. Moreover, for the same change in the compression ratio, the system exergy efficiency increases from 24.54 to 33.93%. The increase in the energy and exergy efficiencies in Fig. 5.79 can be interpreted by the results obtained in Fig. 5.80, at which the exergy destruction rate of the system experiences a deterioration from 290.2 kW to 257.3 kW and the net output work of the system increases from 48 kW to 78.9 kW with the increase in the compressor pressure ratio from 2 to 10.
Fig. 5.78 Variation of the exergy destruction rate in the ORC, gas turbine and combustion chamber with the mass flow rate of natural gas supplied to system.

Fig. 5.79 Variation of the energy and exergy efficiencies of the system with the compressor pressure ratio.
Fig. 5.80 Variation of the exergy destruction rate and the net output power of the system with the compressor pressure ratio.

Fig. 5.81 shows the effect of varying the ambient temperature on the system exergy destruction rate and energy and exergy efficiencies of system 6. The variation of the ambient temperature from 0 to 50 °C leads to an increase in the exergy destruction rate of the system from 260.3 to 252.4 kW and results in a corresponding upsurge in the overall energy and exergy efficiencies of system 6 from 31.7 to 33.88% and from 29.9 to 32.12% respectively. The same variation in the ambient temperature causes an increase in the net output power of the system from 66.38 to 74.32 kW. However, varying the ambient temperature results in an insignificant increase in the ORC and gas turbine output power from 8.534 to 5.582 kW and from 74 to 75.29 kW as shown in Fig. 5.82. Fig. 5.82 also depicts the influence of increasing the ambient temperature on the compressor output power, at which the required compressor power reduces from 28 to 21.2 kW due to the increase of the ambient temperature from 0 to 50 °C. This can be interpreted by the fact that increasing the temperature of the ambient air causes natural preheating for the inlet air resulting in a reduction in the power required to compress the air to the desired temperature and pressure causing an enhance in the overall energy and exergy efficiencies as shown in Fig. 5.79.
Fig. 5.81 Variation of the exergy destruction rate and system overall energy and exergy efficiencies with the ambient temperature.

Fig. 5.82 Variation of the ORC, turbine, compressor, TEG and net system output power with the ambient temperature.
Fig. 83 shows the exergy destruction rate of the main parts in system 6. The combustion chamber is found to have the highest exergy destruction rate of 108.6 kW followed by the TEG system with an exergy destruction rate of 49.16 kW, followed by the ORC system with a total exergy destruction rate of 41.5 kW. The compressor and gas turbine exhibits the lowest exergy destruction rates of 3.548 and 3.52 kW respectively.

![Exergy destruction rate of the main components in system 6 at maximum gas turbine output power of 74.6 kW.](image)

Fig. 5.83 Exergy destruction rate of the main components in system 6 at maximum gas turbine output power of 74.6 kW.

Fig. 5.84 shows the effect of increasing the interest rate on the system exergoeconomic factor and the total cost rate associated with the system. Increasing the interest rate from 2 to 15% results in an increase in the exergoeconomic factor from 25.24 to 36.17%. Moreover, the total cost rate of the system shows an increase from 68.66 to 85.76 $/h when varying the interest rate from 2 to 15%. Fig. 5.85 shows the effect of varying the system lifetime on the exergoeconomic factor and total cost rate of system 6. Rising the expected system lifetime from 5 to 20 years results in a reduction in the exergoeconomic factor from 40.2 to 22.48% and mitigation in the total cost rate of the system from 94.5 to 65.37 $/h.
Fig. 5.84 Variation of the total cost rate and exergoeconomic factor of system 6 with the interest rate.

Fig. 5.85 Variation of the total cost rate and exergoeconomic factor of system 6 with the interest rate.
Table 5.16 shows the results of optimizing the values of the decision parameters in case of maximizing only the exergy efficiency. The selected decision parameters are compressor pressure ratio, interest rate, the molar flow rate of the natural gas, ambient temperature and system lifetime. As shown from the table the optimizing tool increased the compressor ratio and CNG molar flow rate to the upper bound to achieve higher efficiency.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Overall exergy efficiency</th>
<th>Optimum</th>
<th>+20%</th>
<th>Overall exergy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor pressure ratio</td>
<td>16.4</td>
<td>35.34</td>
<td>20</td>
<td>20</td>
<td>35.28</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.124</td>
<td>35.28</td>
<td>0.15</td>
<td>0.14</td>
<td>35.28</td>
</tr>
<tr>
<td>CNG flow rate (g/min)</td>
<td>288</td>
<td>35.28</td>
<td>368</td>
<td>448</td>
<td>35.12</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>38</td>
<td>34.52</td>
<td>50</td>
<td>50</td>
<td>35.28</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>17</td>
<td>35.28</td>
<td>20</td>
<td>20</td>
<td>35.28</td>
</tr>
</tbody>
</table>

Table 5.17 shows the results of optimizing the values of the decision parameters in case of minimizing only the total cost rate of the system, as shown from the table the optimization tool reduced the compressor ratio to the minimum possible value since compressing the air is accompanied with an additional cost on the system.

<table>
<thead>
<tr>
<th>Decision parameter</th>
<th>-20%</th>
<th>Total cost rate ($/h)</th>
<th>Optimum</th>
<th>+20%</th>
<th>Total cost rate ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor pressure ratio</td>
<td>2</td>
<td>13.6</td>
<td>2.095</td>
<td>5.69</td>
<td>14.42</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.02</td>
<td>13.61</td>
<td>0.02026</td>
<td>0.046</td>
<td>15.79</td>
</tr>
<tr>
<td>CNG flow rate (g/min)</td>
<td>48</td>
<td>13.62</td>
<td>49.152</td>
<td>115.2</td>
<td>21.84</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>28.4</td>
<td>34.52</td>
<td>40.4</td>
<td>50</td>
<td>13.62</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>16.9</td>
<td>35.28</td>
<td>19.91</td>
<td>20</td>
<td>13.61</td>
</tr>
</tbody>
</table>
Moreover, the ambient temperature is increased to the maximum possible value to provide natural pre-heating for the system and reduce the required power of the compressor which will result in lowering the cost of compression process of the air. Table 5.18 shows the best values of the decision variables using the multi-objective optimization, the optimum values obtained by the multi-objective optimization is compared to the base values that are considered when designing the system and the values corresponding to the best exergy efficiency and best total cost rate.

Table 5.18 Comparison of optimized parameters and base case using single and multi-objective optimization for system

<table>
<thead>
<tr>
<th>Decision Parameter</th>
<th>Base case</th>
<th>Best exergy efficiency</th>
<th>Best total cost rate ($/h)</th>
<th>Multi-objective best efficiency (35%) and best total cost rate (15$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor pressure ratio</td>
<td>5</td>
<td>20</td>
<td>2.095</td>
<td>12.96</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>0.07</td>
<td>0.15</td>
<td>0.02026</td>
<td>0.02012</td>
</tr>
<tr>
<td>CNG flow rate (g/min)</td>
<td>374</td>
<td>368</td>
<td>49.152</td>
<td>48</td>
</tr>
<tr>
<td>Ambient temperature (°C)</td>
<td>25</td>
<td>50</td>
<td>40.4</td>
<td>50</td>
</tr>
<tr>
<td>System life time (year)</td>
<td>5</td>
<td>20</td>
<td>19.91</td>
<td>19.78</td>
</tr>
</tbody>
</table>

5.7 Integrated Systems Results

In this section, a comparative study is carried out between the proposed integrated system to identify which one of them is more efficient and cost effective, and to identify the exergy destruction rates associated with each system. In Fig. 5.86, the comparison between the energy efficiencies of the 6 integrated systems. System 2 is observed to have the highest energy efficiency of 47.5%, followed by the first system with an energy efficiency of 45.9%, followed by system 4 with an energy efficiency of 38.66% followed by the sixth system and system 5 with an energy efficiency of 32.2% and 32.1% respectively. Finally, the system with the lowest energy efficiency system is found to be system 3, with the energy efficiency of 31.08%. Fig. 5.87 shows the comparison between the exergy efficiencies of the 6 integrated systems. System 2 is observed to have the highest exergy
efficiency of 47.4 %, followed by the first system with an exergy efficiency of 46.4 %.
System 4 comes in the fourth place with an exergy efficiency of 36.2% followed by system 6 with an exergy efficiency of 29.2 % and finally the fifth and third systems found to have an exergy efficiency of 28.9 and 28.85 % respectively.

Fig. 5.86 Comparison between the energy efficiencies of the 6 proposed integrated systems.

Fig. 5.88 shows a comparison between the total cost rates of the 6 systems. System 6 is observed to have the highest total cost rate with a value of 74.7 $/h followed by system 2 and 1 with total cost rate of 65.94 and 64.93 $/h respectively. System 3 has the lowest total cost rate of 14.34 $/h followed by system 5 with 15.36 $/h, and finally, system 4 has a total cost rate of 38.47 $/h. Fig. 5.89 shows a comparison between the exergoeconomic factors of the six systems. System 3 is found to have the highest exergoeconomic factor of 42.8% followed by system 5 with an exergoeconomic factor of 40.1%. The first system and second systems have an exergoeconomic factor of 33.47 and 33.08 % respectively. The six system found to have an exergoeconomic factor of 29.67%. Finally, the lowest exergoeconomic factor is found in the fourth system with a value of 28.8%.
Fig. 5.87 Comparison between the exergy efficiencies of the 6 proposed integrated systems.

Fig. 5.88 Comparison between the total cost rate of the 6 proposed integrated systems at maximum systems output power of 118 kW.
Comparison between the exergoeconomic factors of the 6 proposed integrated systems at maximum systems output power of 118 kW.

Table 5.19 shows a comparative evaluation for the six proposed systems. The evaluation includes the energetic and exergetic efficiencies, exergy destruction of each system. Expected emission released from each system per kWh, total cost rate, estimated purchase cost and the exergoeconomic factor of each system are also incorporated in the table. Table 5.20 shows a comparison between fuel tank capacity, vehicle range, weight, fuel consumption and emissions for the six introduced systems. The fuel tank capacity and vehicle range for each system are calculated based on the ICE energy that can be obtained from a typical SUV fuel tank that contains 53 L of gasoline [109], at which the fuel tank capacity for each system can provide the same output energy as in the previously mentioned reference. System 2 is observed to have the longest driving range due to the hydrogen that is generated on board using the AEC unit. Gross vehicle weight for each system is calculated using ADVISOR software, weights of the components that are not existing in the software are assumed. Table 5.20 also shows fuel consumption in the case of combined driving mode [city and highway driving]. Moreover, the estimated emissions per km for each system are also incorporated.
Table 5.19 Comprehensive comparison of the six systems including energetic, exergetic, environmental and cost measures

<table>
<thead>
<tr>
<th>No</th>
<th>System configuration</th>
<th>$\eta$ [%]</th>
<th>$\psi$ [%]</th>
<th>$\dot{E}xd$ [kW]</th>
<th>Emissions [g/kWh]</th>
<th>Total cost rate [$/h$]</th>
<th>Estimated capital cost [K$]</th>
<th>$f$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Battery-Fuel cell-PV</td>
<td>45.9</td>
<td>46.4</td>
<td>122</td>
<td>0</td>
<td>64.93</td>
<td>48.97</td>
<td>33.47</td>
</tr>
<tr>
<td>2</td>
<td>Battery-Fuel cell-PV-AEC</td>
<td>47.5</td>
<td>47.4</td>
<td>124.6</td>
<td>0</td>
<td>65.94</td>
<td>49.5</td>
<td>33.08</td>
</tr>
<tr>
<td>3</td>
<td>ICE-DSU</td>
<td>31</td>
<td>28.8</td>
<td>168.3</td>
<td>$N_2$ [0.985]</td>
<td>14.34</td>
<td>12.40</td>
<td>42.8</td>
</tr>
<tr>
<td>4</td>
<td>ICE-DSU-Fuel cell</td>
<td>38.6</td>
<td>36.2</td>
<td>178.7</td>
<td>$N_2$ [0.642]</td>
<td>38.47</td>
<td>20.35</td>
<td>36.18</td>
</tr>
<tr>
<td>5</td>
<td>ICE-TEG-AEC</td>
<td>31.1</td>
<td>28.9</td>
<td>255.7</td>
<td>$N_2$ [0.985]</td>
<td>15.36</td>
<td>16.40</td>
<td>40.1</td>
</tr>
<tr>
<td>6</td>
<td>Battery-GT-TEG-ORC-ACC</td>
<td>32.3</td>
<td>29.2</td>
<td>266.9</td>
<td>$CO_2$ [0.1763]</td>
<td>74.7</td>
<td>49.25</td>
<td>29.67</td>
</tr>
</tbody>
</table>

Table 5.20 Comparison of fuel tank capacity, vehicle range, weight, fuel consumption and emissions for the six systems

<table>
<thead>
<tr>
<th>No</th>
<th>System configuration</th>
<th>Type of fuel</th>
<th>Fuel tank capacity</th>
<th>Vehicle Range [km]</th>
<th>Gross vehicle weight</th>
<th>Fuel consumption [combined city/hwy mode]</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Battery-Fuel cell-PV</td>
<td>$H_2$</td>
<td>5.6 [kg]</td>
<td>744$^a$</td>
<td>2275$^*$</td>
<td>0.82 [kg/100 km]</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Battery-Fuel cell-PV-AEC</td>
<td>$H_2$</td>
<td>5.6 [kg]</td>
<td>794$^b$</td>
<td>2300$^*$</td>
<td>0.823 [kg/100 km]</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>ICE-DSU</td>
<td>$NH_3$</td>
<td>129.5[L]</td>
<td>680</td>
<td>2225$^*$</td>
<td>19 [L/100 km]</td>
<td>$N_2$ [7.95 g/km]</td>
</tr>
<tr>
<td>4</td>
<td>ICE-DSU-Fuel cell</td>
<td>$NH_3$</td>
<td>84.5[L]</td>
<td>680</td>
<td>2400$^*$</td>
<td>12.4 [L/100 km]</td>
<td>$N_2$ [5.13 g/km]</td>
</tr>
<tr>
<td>5</td>
<td>ICE-TEG-AEC</td>
<td>$NH_3$</td>
<td>129.5[L]</td>
<td>680</td>
<td>2250$^*$</td>
<td>19 [L/100 km]</td>
<td>$N_2$ [7.95 g/km]</td>
</tr>
<tr>
<td>6</td>
<td>Battery-GT-TEG-ORC-ACC</td>
<td>CNG</td>
<td>150 [L]</td>
<td>680</td>
<td>2550</td>
<td>22 [L/100 km]</td>
<td>$CO_2$ [130 g/km]</td>
</tr>
</tbody>
</table>

* obtained from ADVISOR software

$^a$ 744 represents 680 km + 64 km due to hydrogen saved by PV
$^b$ 794 represents 680 km + 113.65 km due to hydrogen generated onboard by AEC
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions
Six novel integrated energy systems are conceptually developed to function as a potential powering options for vehicle applications. Systems are analyzed using energy and exergy approaches along with a parametric study to see the effect of varying different designing and surrounding parameters on the performance of the introduced systems. Systems 3 and 5 are analyzed dynamically to mimic the performance of the vehicle powering system during an actual driving cycle. The purpose of the introduced integrated energy systems is to provide a potential environmental clean transportation option to replace the current fossil fuel vehicles. Energy, exergy efficiencies and exergy destruction rate of the overall systems and systems main units are evaluated and determined. In this regard, the following findings are summarized from the current study:

- Using PV arrays in system 2 showed encouraging results as the AEC could produce 5.2 g/min of hydrogen at 10 bar on board, while system 1 could save the consumption of hydrogen by 2.963 g/min at the same PV input energy of 16 kWh.
- The overall energy and exergy efficiencies of system 1 are found to be 45.96 % and 46.37 % at a fuel cell current density of 1150 mA/cm² respectively.
- The overall energy and exergy efficiencies of system 2 are found to be 47.55 % and 47.44 % at a fuel cell current density of 1150 mA/cm² respectively.
- The maximum exergy destruction rates in systems 1 and 2 occur in the fuel cell stack with 122 and 124.6 kW respectively, at a current density of 1150 mA/cm² and maximum power output of 118 kW. Moreover, the exergy destruction rate in the AEC unit reached 2.4 kW at a current density of 250 mA/cm².
- The overall energy efficiencies of systems 3 and 4 are obtained as 31.08 % and 38.66 % respectively at maximum traction power of 118 kW.
- The vehicle maximum speed in system 3 is found to be 185 km/h with maximum gradability of 25.65% and maximum acceleration of 1.098 m/s² at the second gear.
- The overall exergy efficiencies of systems 3 and 4 are found to be 28.85 % and 36.2 % respectively at maximum traction power of 118 kW.
• The maximum exergy destruction rates in systems 3 and 4 are found to be 168.3 and 178.7 kW respectively at system maximum output power of 118 kW. The exergy destruction rate of the fuel cell in system 4 is found to be 68.3 kW.

• DSU unit succeeded to minimize the exergy destruction rate in system 3 and system 4 by 23.9 and 53 kW respectively when the two systems are operating at maximum power traction of 118 kW.

• The maximum amount of the hydrogen that can be saved from the DSU in system 3 after deducting the hydrogen supplied to the ICE from the total hydrogen produced is 1.076 mole/s with an ICE running at a maximum power of 118 kW.

• The maximum amount of the hydrogen that can be supplied to the fuel cell from the DSU in system 4 is 37.87 mole/min with an ICE running at a maximum power of 65 kW.

• The overall energy and exergy efficiencies of system 5 are found to be 31.1% and 28.94% respectively at a maximum engine power of 118 kW.

• In system 5, the power obtained from the TEG system and supplied to the AEC unit was sufficient to provide the required hydrogen to the ICE to achieve appropriate combustion characteristics and better engine performance.

• The vehicle maximum speed in system 5 is found to be 180 km/h with maximum gradability of 25.35% and maximum acceleration of 1.084 m/s² at the second gear.

• The maximum engine power in system 5 is found to be 118 kW at 6500 r.p.m and maximum engine torque of 216.8 N.m at 3300 r.p.m.

• The TEG maximum energy and exergy efficiencies in system 5 are found to be 8% and 14.32% at a maximum engine power of 118 kW.

• The maximum amount of hydrogen that could be produced from the AEC unit in system 5 is 6.246 mole/min at maximum engine power of 118 kW and AEC operating current density of 0.25 A/cm².

• The exergy destruction rates of the ICE, TEG, and AEC in system 5 are found to be 199.5, 23.9 and 3.1 kW respectively at a maximum engine power of 118 kW.

• The overall energy and exergy efficiency of system 6 are found to be 32.3 and 29.21% respectively.
• The overall exergy destruction rate in system 6 is found to be 266.9 kW, and the higher share of the exergy destruction rate is found in the combustion chamber with a value of 108.6 kW at maximum turbine output power of 74.88 kW.

6.2 Recommendations

This section focuses on providing recommendations for further studies that might follow the presented work in this thesis. The work presented in this thesis is novel where it takes the concept of energy systems integrations and applies it to domestic transportation systems to reduce the energy consumption and mitigate the transportation overall environmental impact. To develop the study to a wider perspective and expand the usage opportunities for the proposed systems, the recommendations are listed below:

• Carrying out life cycle assessments for the proposed systems is necessary to confirm that the operational emissions produced by the proposed vehicles are minimal compared to the overall life cycle emissions.

• Building prototypes for the proposed vehicle systems is essential to investigate and compare their actual performances with the results obtained from the current thermodynamic analysis. Building prototypes is also necessary since it can motivate the automotive industry to promote the proposed systems to the commercialization stage.

• Integrating regenerative braking systems supported by super-capacitors with the proposed systems where applicable, is necessary to increase the efficiency of the proposed systems and enhance the recovery of waste energy.

• Implementing other powering options such as pneumatic systems should be considered since they have zero emissions and operating using compressed air, which can be obtained via various processes operating with the different sources of renewable energy.

• Applying electrochemical compression method to compress hydrogen onboard is required because such technology can allow for storing hydrogen onboard at very high pressures.

• Performing dynamic modeling for the proposed systems that are not analyzed dynamically in the thesis should be done to evaluate their actual performances and the released emissions during the different phases of the driving cycles. Other driving cycles such as NEDC and FTP can also be considered for deeper investigation.
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