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Solid Oxide Fuel Cell Hybrid Systems as a Distributed Cogeneration Solution

A dissertation submitted by

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Abstract

This paper is on the topic of *Solid Oxide Fuel Cell Hybrid Systems as a Distributed Cogeneration Solution*. Broadly, the key outcomes of this paper aim to understand the hybrid system solid oxide fuel cell (SOFC) technology combined with micro gas turbine (mGT) plant. To achieve this, research was collated in the Background Information section on the fundamentals of the solid oxide fuel cell variant, interconnected cells that form stacks, stack level operating principles, relevant fuel types and the system's fuel-flexibility. An overview of gas turbine technology and the principles underpinning operation, and finally hybrid system formed including research into coupling (physical, electrical and thermal) and start-up process of the complete hybrid system was completed.

The Methodology was developed in two parts. The first Methodology section demonstrates the system advantages in the context of environmental metrics such as plant/fuel efficiencies, time-of-use, start-up timing and emissions. These are highlighted as key advantages by means of comparison drawn from other relevant generation systems, such as photovoltaic, coal-fired, combined cycle gas turbine and conventional large gas turbine plant. In the second part of the methodology, the system is specified and modelled against defined load and supply factors that affect resulting assessment of the utilisation of this system in the two applications.

The Result and Discussion section demonstrates the key outcomes of the Methodology in the context of the Background Information section. Briefly, these include highlighting the efficiency increases that result from combining the SOFC plant with mGT plant, approximated as an increase from 30% as a stand-alone SOFC system, to 55% net electrical efficiency for the SOFC/mGT hybrid (Section 3.2.1), not including further benefits of recuperating thermal energy from the output of the plant as considered in Section 3.4 within "Application to Use-Cases". Also, the competitive 40 minute start-up time for the SOFC/mGT system (Section 3.2.2) and non-restricted time-of-use advantages (Section 3.2.3) are highlighted. Finally, figures accounting for emissions factors within fuel types combined with plant efficiencies highlighted overall low emissions for the SOFC/mGT as modelled in Section 3.2.4. The results of the second part of the Methodology are detailed within Section 4.0 to assess how the SOFC/mGT system is integrated in hypothetical use-cases, noting assumptions made regarding load and supply factors to achieve this.

The sections of the paper, inclusive of all research, modelling and analysis of results, as detailed, support the original aims of the project in terms of understanding the utilisation of highly efficient SOFC/mGT hybrid plant in context to its application as a distributed cogeneration solution. While this system is in early stages as both the Limitations and Further Work section discuss, this particular hybrid may form part of the future energy generation and distribution landscape, with key peak-reduction and time-shift advantages evident.

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Nikolas Zanetich

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Foreword

Coming into the final year of the BENH program, I had the intention of undertaking a body of work that would allow understanding of a topic within the electrical engineering discipline that I would have otherwise not been exposed to. Being from a hands-on trade background as an electrician, and currently working as an electricity systems designer for Ergon Energy, I had no exposure to the fuel cell technology that I had read about in AEMO, ARENA and Engineers Australia articles. After doing a decent amount of initial research on fuel cells and the role the technology had in the future of both stationary and mobile power systems, I decided to commit to a final year dissertation around the Solid Oxide variant. After conducting further reading down the fuel cell *rabbit hole* pre-Semester 1, and coupled with understanding the objectives of both ENG4111 and ENG4112, I decided that I would narrow down my topic selection again with the aim of shedding light on a technology that I initially estimated as future-viable but currently undiscovered. Hence, I made a commitment to understand the niche topic of *Solid Oxide Fuel Cell Hybrid Systems as a Distributed Cogeneration Solution.*

The result of this commitment has been two semesters of consistent effort, lost sleep, the cliché *blood, sweat and tears*. Raw time in the seat, digging deep, every day *except when I just absolutely needed a break*; and here I am, with a finalized final year dissertation. Without completely capitulating, I have seen first-hand my mental and emotional limits of delivering a body of work of this focus and volume, simultaneously with life happenings. To note, as well as better understanding of this topic, I uncovered a deep appreciation of academic work and achievement, particularly the intensity of detail to which higher research levels would demand in their academic papers. I can say with complete confidence that I have absolutely put my best foot forward, my best effort, into my work and final year studies this year, and I hope that this paper is received as an example of such.

Thank-you to Les Bowtell and Ken Ash for supporting me and keeping me sane throughout, and of course my family, for everything.

Nik Zanetich

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1.0 Introduction

1.1 Topic Introduction

The topic of this dissertation is *Solid Oxide Fuel Cell Hybrid Systems as a Distributed Cogeneration Solution.* This is a timely and relevant area of research for both academic institutions and industry, where there are obvious challenges in the medium term for the energy sector particularly due to factors like the retiring of large synchronous coal-fired plant which have traditionally powered the state (Engineers Australia 2016), the global push to significantly reduce green-house gas (GHG) emissions (UN 2020), and the increasing uptake of electric vehicles (EV's) (Electric Vehicle Council 2019), all of which will add stress to the current equilibrium of energy supply/demand at the network level. Due to factors such as these, there is ubiquitous acknowledgement within academia and industry that the energy generation systems of the future will need to have several key features, including:

- significantly reduced GHG emissions (Abdallah & El-Chennary 2013);
- emphasis on system stability to bolster network reliability (AEMC 2020);
- economic viability (Keeley & Managi 2019);
- a distributed nature, with an emphasis on cogeneration applications to maximize energy efficiencies (AEMC 2020);

One such combined heat and power (CHP) system that could assist in the global push towards better, cleaner methods of energy production is the hybrid fuel cell system integrating Solid Oxide Fuel Cells with Micro Gas Turbine technology. These systems are known as SOFC/mGT systems and offer several key advantages particularly in terms of high energy efficiency, fast start-up time, unrestricted time-of-use, and low emissions (Damo et al. 2018). These environmentally obvious benefits as well as fuel flexibility, supply reliability, frequency stability (due to inertia of rotating turbine machinery) (AEMC 2020) and stand-alone capability means this fuel cell hybrid system has the potential to be utilised as a distributed cogeneration solution.

With growing energy demand projected in the medium term due to electric vehicle uptake, there is an increasing need to look at how power is being supplied. Coupled with aging infrastructure designed to historic power requirements where electric vehicles were not considered in daily load profiles, coupled with the global push towards significantly curbing greenhouse gas (GHG) emissions, industry must review the way it is generating and distributing power. Key to this is the emphasis on more efficient, cost-effective distributed generation systems (AEMO 2019), such as that potentially offered by the SOFC/mGT system.

1.2 Aims and Objectives

This paper intends to research and model the potential of hybridised solid oxide fuel cell and micro gas turbine hybrid technology in the context of providing a distributed and localised energy generation solution.

The key outcomes of this research project aim to:

- Understand the fundamentals of SOFC and mGT technologies;
- Understand the design and operating principles of hybrid SOFC systems;

- Validate this system throughout in terms of sustainability metrics;
- Model the hybrid SOFC system as an energy efficient generation system;
- Model this system as integrated into the localised network;
- Assess the utility of Hybrid SOFC systems for localised generation purposes;

Overall, the aim of this paper is to review current and historic research surrounding solid oxide fuel cells and micro gas turbine technologies, understand the potential role these technologies play in future co-generation, distributed energy generation, and to model these situations on the household and distribution level, with specific use-cases, to offer insight into how this system would be integrated to supply electricity and thermal demand.

1.3 Relevance of the Thesis

There is growing support for alternative sources of generation within Australia and while SOFC/mGT hybrid systems are currently at demonstration stage, there are certain key advantages to this system that would support it being included in the modern distributed generation landscape. To highlight the appropriate timing of research of the SOFC/mGT hybrid, a recent announcement was made by the Australian Government of $1.9 billion dollars towards supporting "new and emerging" technologies in Australia (Australian Government 2020), which is inclusive of developments made in systems that utilise fuel cells such as the SOFC/mGT hybrid system discussed in this paper.

2.0 Background Information

2.1 Household Energy Demand in an Electric Vehicle Future

As a benchmark, the electricity demand in Australia averages at 15.2kWh per household per day (Ausgrid, 2018), varying with climatic and geographic conditions. A substantial increase in household electricity consumption is projected as more households opt for electric vehicles in the short to medium term (Energeia, 2017), introducing problems associated with charging such as amplifying peaks within the daily load profile (Sioshansi, 2018). In 2018, Australians purchased 2216 electric vehicles (Schmidt, 2019). To add tangible support to this growth, government bodies have set electric vehicle targets, such as NSW aiming to compose 10% of their fleet with electric vehicles (Electric Vehicle Council, 2019). It is important to note the magnitude of the uptake of electric vehicles; $300 USD billion has already been invested in the electrification of global vehicle models (Electric Vehicle Council, 2019). And with model availability increasing, future electric vehicle uptake is only projected to increase.

With an increase in electric vehicles inherently comes an increase in electricity demand from charging. In terms of capacity, current electric vehicle models range in capacity from approximately 25kWh with the Nissan Leaf kWh (Nissan, 2020) to 100 kWh in the Tesla Model S 100d (Tesla 2020). A fraction of this would be used on a consistent, daily basis; assumptions can be made of the daily average electric vehicle charging requirements based on the model and kilometers travelled, which differs depending on the demographic and geography of EV owner-drivers. For all intents and purposes, an average of 0.2kWh per km (including charging losses) is consumed by electric vehicles, with approximately 14'000 km per year driven by the average driver (ABS 2019); averaging at 40 km per day per driver; netting an average energy consumption of 8kWh per day from average EV usage. Additionally, these figures are considered in a pre-Transport-as-a-Service (pre-TaaS) societal situation where autonomous vehicles and transport pooling is not available, so future daily energy usage could be significantly more than this figure suggests (Arbib & Seba 2017).

An increase in EV households of an additional 8 kWh of energy required per day is not isolated – this demand on a household level is electrically tied to the generation source it is fed from via the distribution network. Therefore, adding an additional load of 8kWh of household demand per day essentially means an 150% expected demand on the network. This projection is a conservative case; in many situations outside of consumer driven electric vehicles exists many private and government level EV fleets which would undoubtably move this demand upward of the 150% average, considering these business fleets account for 63% of total electric vehicle sales (Electric Vehicle Council, 2019). From a utility perspective, significantly increasing demand on the distribution network necessitates significant additional investment in network assets.

2.2 Alternative Generation – Fuel Cell Technology

Renewable energy research developments have identified fuel cell technology playing an important role as an energy source in the future (Staffell 2018). In short, fuel cells are a renewable energy type which converts chemical reactions between hydrogen and oxygen into an electrical potential. Due to several key advantages such as high energy efficiency, fuel flexibility and applications within a wide range of operating temperatures (Viessmann 2020), fuel cell technologies offer competitive power generation which can be easily implemented in extensive applications.

Early fuel cell technology research began in the 1930's with the experimentation of solid oxide electrolytes at high temperature operation by Swiss scientist Emil Baur (Smithsonian 2014). Since that time, developments in research have allowed many fuel cell variants to emerge. These include the Phosphoric Acid Fuel Cell (PAFC), Proton Exchange Membrane Fuel Cell (PEMFC), Molten Carbonate Fuel Cell (MCFC), microbial fuel cell, Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC) and Solid Oxide Fuel Cell (SOFC) (Energy.Gov 2020). Of these, PEMFC, DMFC and PAFC are classed as low-temperature and are understood to have applications in transport applications, while PAFC, MCFC and SOFC variants are suitable to high temperature stationary power generation applications.

Among the high-temperature fuel cell types, SOFC's are the most widely developed. This is due to the SOFC variant having high efficiency, electrolyte versatility and the flexibility of using different hydrocarbon fuels (Ferrari 2010). This technology has become the most attractive fuel cell application in combined heat-power generators, as well as in the building services sector. By recuperating heat that would have otherwise been lost, SOFC technology has been used in many instances to provide thermal applications, for example, in residential homes. Many parallel scientific and engineering aspects relevant to fuel cells have been reviewed and researched over the past 10 years, particularly in the last five years which indicates growing interest in this research area.

Developments in understanding and improving SOFC technologies have been mainly conducted based on modelling and simulation studies with the aim to achieve better operational performance. Research in this topic has been developed in several areas involving improved model and observer studies (Laurencin 2007), advanced estimation and identification (Jayasankar, 2008), precision of control and management (Moghaddam 2011), and optimization of design and operation (Palazzi 2007). Note that many of these studies frequently compare SOFC's to other fuel cell types such as PEMFC and MCFC (Bozorgmehri 2012) in order to demonstrate the effectiveness of the SOFC variant.

Hybrid system variants that capitalize on thermal and electrical energy production and reuse do so by integrating SOFC technology with other compatible energy generation technology, such as micro gas turbines (Palsson 1999). As a generation source, fuel cells provide an alternative means of generating energy than conventional rotating machine sources, such as in gas, diesel or coal power generation facilities. Advantages include capacity to cogenerate along other generation types, either on a small scale level with integrated hybrid systems, or in the wider grid level, where the likes of AEMO allow the integration of various generation sources to supply the energy demand of Australia (AEMO 2019).

2.3 Solid Oxide Fuel Cells (SOFC)

2.3.1 SOFC Overview

Solid oxide fuel cells (SOFC) are a high-temperature, solid-state electrochemical conversion device that produces electricity directly from the electrochemical oxidation reactions. Typically, a cell operates at a temperature range of 600 to 1000 degrees centigrade (Ferrari 2017), at which temperature ionic conduction of oxygen ions takes place. SOFC are one of the most efficient devices to convert fuel chemical energy directly to electrical energy with efficiency values in the 50-55% range (Ferrari 2017).

2.3.2 SOFC – Cell Level

These type of fuel cells are comprised of an anode, cathode and a solid oxide ceramic electrolyte. A single SOFC is made up of four layers, three of which are ceramics, stacked together that are only a few millimeters thick (Dwivedi, 2019).

2.3.2.1 Anode

The ceramic anode layer is selected to have high porosity to allow mass transport of gases, namely, to allow fuel to flow towards the electrolyte. It also must exhibit high electrical conductivity and adequate ionic conductivity such that ions contact with the fuel flow. This material is a cermet, which is made of nickel and the specific ceramic material used for the electrolyte of the cell, which is typically YSZ (yttria stabilized zirconia) nanomaterial-based catalysts; commonly, this is $Ni\text{-}ZrO_2$ (Dwivedi, 2019). The nickel exhibits high electrical conductivity and stability under chemical reduction conditions. Zirconia is used to both inhibit the sintering of the metal particles and to provide a thermal expansion ratio similar to the electrolyte. Of the cell layers, the anode is the strongest and thickest and provides the mechanical properties of the individual SOFC cell (Ferrari 2017).

2.3.2.2 Cathode

The cathode is commonly Sr-doped LaMnO3 material, known as strontium-doped lanthanum manganite. This material forms a porous structure that facilitate mass transport of gases. Alternate materials exist, including P-type conducting perovskite structures that display mixed ionic and electrical conductivity. However, it is typical that the modern fuel cell is made of strontium-doped lanthanum manganite (Dwivedi, 2019).

2.3.2.3 Electrolyte

The defining feature of a SOFC is the ceramic electrolyte. The majority of SOFC developers use electrolytes made of zirconia stabilised with a small amount of yttria, namely YSZ (Dwivedi, 2019). When raised to operating temperatures of more than approximately 800 degrees centigrade, the electrolyte become good conductors of oxygen ions while being minimally conductive (Ferrari 2017). These means that selection of material to form the electrolyte (and anode, cathode) is difficult as only a specific range of available materials share these characteristics. Of note, by not using a liquid electrolyte, SOFC avoid the typical material corrosion and electrolyte management issues inherent to other electrochemical means of producing or storing energy.

2.3.3 SOFC Operation

Solid oxide fuel cells operate by reducing oxygen at the cathode-electrolyte surface (Figure 1), which then form oxygen ions that are transported to the electrode through the electrolyte (Dwivedi 2019). Once these ions arrive at the anode-electrolyte surface, these oxygen ions react with the hydrogen ions to form water, which is released from the SOFC stack as exhaust steam (Ferrari 2017). Electrons are released at the anode and flow though the external load to the cathode, where they are used to reduce the oxygen molecules (Dwivedi 2019).

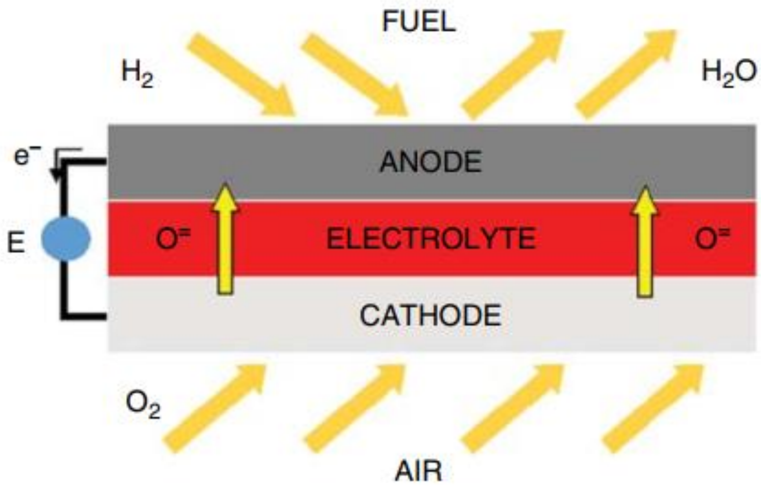

Figure 1: Electrochemical Process within a Solid Oxide Fuel Cell (Ferrari et al. 2017, P. 13)

2.3.4 SOFC Stack

2.3.4.1 Cell Interconnector

A SOFC stack is comprised of hundreds of these cells connected in series and require very high temperatures (500 - ~750 – 1000 degrees) to become electrically/ionically active (Ferrari 2017). Solid oxide fuel cells are physically connected to form 'stacks' by means of an interconnector. This interconnector is commonly a material such as lanthanum chromite, as it enables a higher current to travel between paralleled fuel cells (Ferrari 2017). Other interconnector materials can be used, however because of inherent SOFC properties of operation such as high temperature and the use of electrochemical reduction can cause issues such as thermal expansion issues, cathode poisoning and oxidation of metal (Ferrari 2017). For this reason, lanthanum chromite is the favoured material for SOFC interconnectors (Ferrari 2017).

2.3.4.2 Tubular Stack Geometry

SOFC stacks are formed primarily in either of two geometries: planar or tubular. Tubular geometry is named after the laboratory test tube, where it takes its form: the outer surface of the cell is the anode side of the cell, and the cathode side lines the solid oxide electrolyte (see Figure 2). Air is injected into the inner tube from the guidance tube which is composed of alumina (Ferrari 2017). The preheated air is injected into the bottom of the cell tube and flows over from the cathode surface of the cell tube through the gap between the injection and cell tubes, with the end of the tube closed. Fuel gas flows over this anode surface amongst the cell tubes through the gap (Ferrari 2017). Oxygen ions pass via the cathode and electrolyte and reacts with fuel to create current (hydrogen reaction). Tubular SOFC's are advantageous in that they can use a variety of hydrocarbon-based gases (and their synthetic derivatives) such as natural gas, biomass and coal for use as fuel sources. The disadvantage of tubular compared to their planar counterpart is that the ohmic losses are much higher (Ferrari et al. 2017).

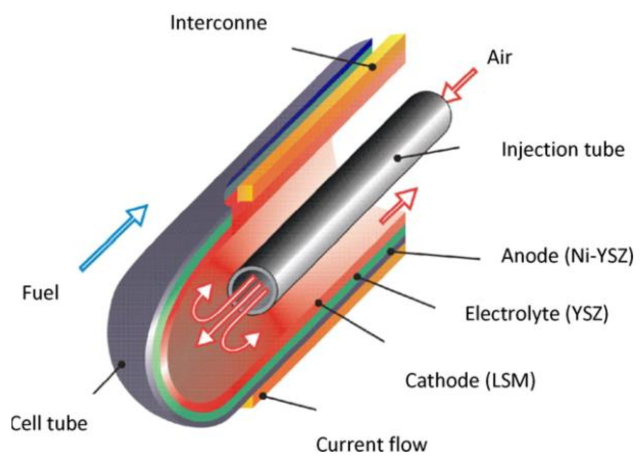

Figure 2: Structure of the Tubular Solid Oxide Fuel Cell (Hussain et al. 2010, P. 1896)

2.3.4.3 Planar

Aside from the tubular SOFC configuration, the planar configuration is essentially constructed of plates (Figure 3). The positive electrolyte-negative electrode (PEN) forms a cell with use of an interconnector placed above and below the cell stack, with air and fuel channels. The anode and the separator plate allow the fuel gas channel, and the cathode and separator plate place the air channel (Ferrari 2017). The planar configuration is advantageous in its low-cost, manufacturing simplicity at high volume, as well as high volumetric power density due to a large surface area allowing greater current flow. For these reasons, most cell manufacturers concentrate on the planar configuration (Ferrari 2017). The disadvantages with the planar geometry are obtaining a mechanically stable structure as thin layer ceramics are inherently susceptible to failure when subjected to moderate stresses, as well as a more undesirable start-up time (Ferrari 2017).

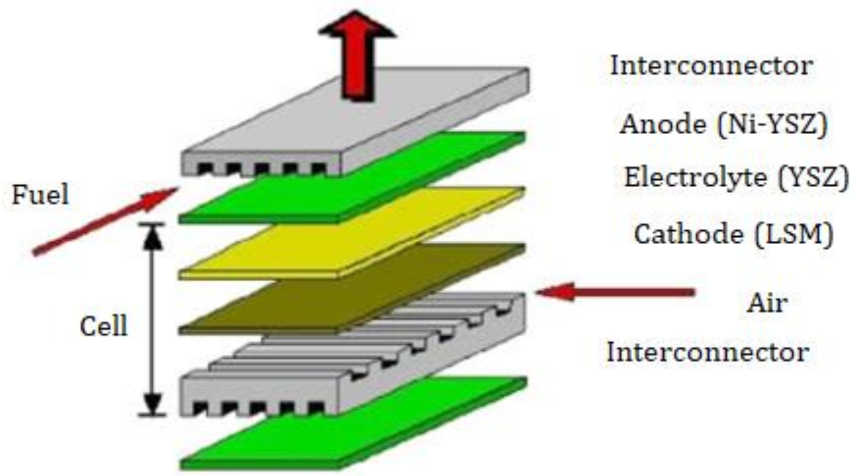

Figure 3: Planar Solid Oxide Fuel Cell Configuration – Cell Level (Hussain et al. 2010, P. 1897)

2.4 SOFC Systems

2.4.1 SOFC Systems Overview

SOFC systems (Figure 4) find their main application in stationary power generation, such as applications in distributed generation grids (Moghaddam 2011). The suitability of these SOFC to stationary applications is due to the long startup and shutdown phase times related to their high operating conditions, which have to be designed and controlled to not cause excessive thermal stresses to the stack; nominally, to not exceed a gradient of 3K/min (Ferrari 2017). Even still, the applicability of SOFC systems and their hybrid variations pose a unique opportunity to the future of energy generation, in terms of heat and electricity on both the household and distribution level (Moghaddam 2011).

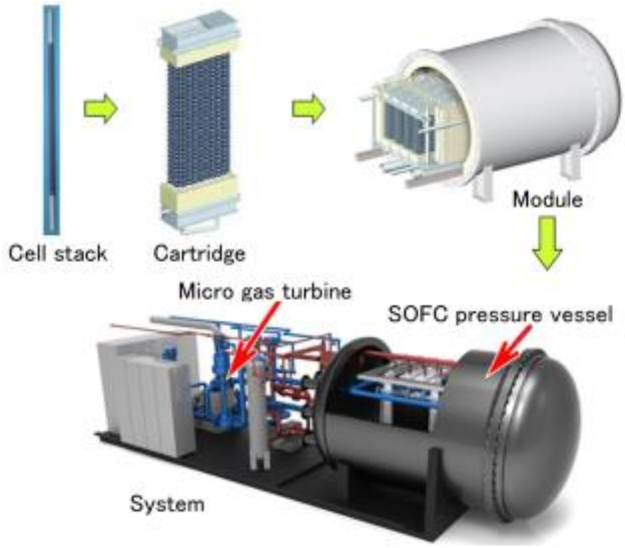

Figure 4: SOFC Components and Hybrid Micro Gas Turbine Plant (Mitsubishi Heavy Industries 2015, P. 112)

2.4.2 High Temperature SOFC systems

SOFC systems have been developed to run at high temperature conditions, typically between 600 and 1000 degrees centigrade. These temperatures remove the need for noble metal-based catalysts, which removes the problem of carbon monoxide (CO) poisoning (Haga 2008). Also, at high operating temperatures the system enables adequate electrochemical reactions directly on CO and CH_4 gases which are usually present in reformed gas flows (Ferrari 2017). This is important as a high-temperature SOFC system removes the need for complex fuel cleaning components, which are present in low temperature fuel cell technology (Ferrari 2017).

2.4.3 SOFC Systems Fuels

High temperature operating conditions allow for greater internal fuel reforming operations, and allow use of a wider range of fuels, selection of which is dependent on an ideally significant hydrogen content (Ferrari 2017). While SOFCs using standard commercial fuels are not able to efficiently operate as electrochemical reactors limited due to kinetic aspects, they are able to accept fuels including CH4, CO and natural gas, the latter of which would be selected based on the reactor designed and installed as part of the SOFC system in order to produce hydrogen-rich gases (Lee, 2017). This is an important consideration of SOFC systems: while fuel processing reactions can be carried out upstream of the plant fuel intake duct, integrated configurations are worth consideration as they have the added benefit of being able to exploit the heat generated by SOFC reactions and/or the steam content available at the exhaust ducts (Al-Khori 2019). A system designed with integrated fuel reforming process means a large overall benefit in energy efficiency, and associated cost reduction, as the heat content produced by these SOFC reactors can be redirected and utilised internally within the system (Ferrari 2017). As an external component of the wider SOFC hybrid system, this fuel processing reactor is termed the 'pre-former' when used with natural gas, with most fuel processing reactions carried out internally in the SOFC. These internal reforming processes take two configurations, namely indirect reforming (IIR) where the reactor is located (only) in thermal contact with the fuel cell, and direct internal reforming (DIR) where the fuel processing reactions are carried out directly inside the anodic ducts of the stack (Ferrari 2017).

2.5 Gas Turbines

2.5.1 Gas Turbines Overview

Gas turbine technology is long standing and well understood. Currently, gas turbines accounted for 55'000 GWh of energy production Australia wide in 2017 (Energy Gov 2018), which makes up approximately 13% of the power produced for consumption in Australia (Origin 2018). Initial gas technology began with a three-cylinder machinery running 3% thermal efficiency (Brittanica 2020). Today, the world's largest gas turbine GE's "Harriet" is approximately 600 MW in size and runs at 61% efficiency with minimal emissions (Maxey 2015). Large leaps and bounds in both thermodynamic, machinery and electrical integration aspects have allowed this technology to make its progress to what we see today. In more recent times, there has been the scaling back of gas turbine technology to allow potential for smaller generation points. This shift has meant opportunities open for distribution generation avenues and especially well suited, considering start-up times of gas are significantly shorter than that of other competing rotating machinery generation (ARENA 2018). Additionally, while still being primarily fossil fuelled with natural gas, turbine technology are also more energy efficient than other fossil fuel generation systems – with 60% efficiency for typical natural gas combined-cycle power plant and 42% efficiency for typical gas-fired plant, as compared to the average of 33% efficiency for typical coal-burning power plant (National Academy of Science 2020).

2.5.2 Micro Gas Turbine (mGT) Operating Principles

Micro Gas Turbines (mGT) are gas turbines that are classed with operating capacities that are less than 1 MW in plant size (Gurrappa, I 2010). For micro gas turbines, due to practical limitations the most widely used thermal cycle for is the recuperative cycle without intercooling/reheating. The operation of gas turbines is represented by the Joules-Brayton cycle (Nascimento et al. 2013). This cycle is based on four cycles: two processes at constant entropy, which are compression and expansion, and also two processes at constant pressure, which are heat addition and rejection (Figure 5).

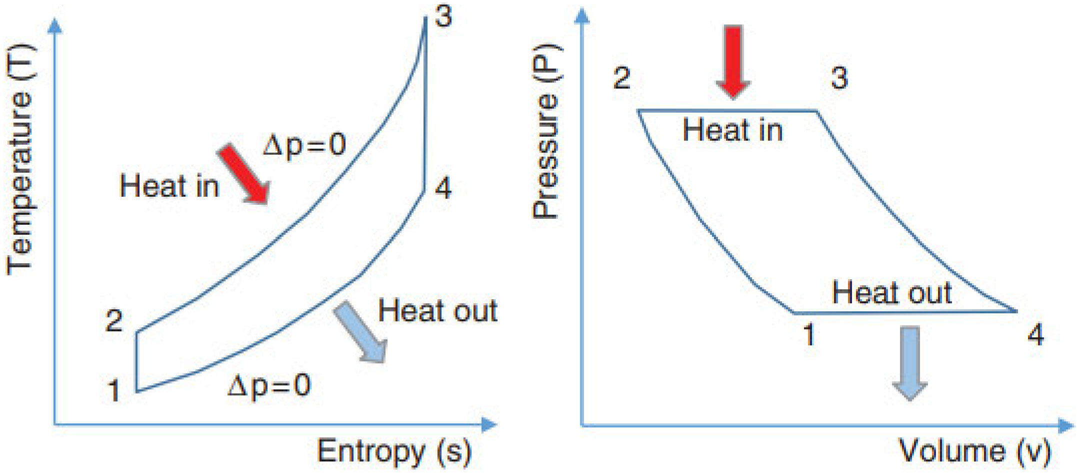

Figure 5: Joules-Brayton Cycle Diagrams, Temperature-Entropy (Left), Pressure-Volume (Right) (Ferrari et al. 2017, P. 60)

The recuperative cycle whereby the system is designed to recuperate exhaust heat from the operation of the gas turbine system and employs this heat energy in the operating cycle (Weiland 2017). The recuperated Brayton cycle is based on exactly this approach, where a heat exchanger (recuperator) is used to transfer sensible heat from the turbine exhaust gases to the air delivery of the compressor, which work to increase the temperature of the latter and reduce the amount of heat added to the cycle (Ferrari 2017). This approach is especially effective where the temperatures of at the compressor air inlet and the turbine exhaust gases are significant. Combined with SOFC technology, there are a number of other ways this exhaust heat can be redirected for overall system optimisation/ utilisation (Palsson 1999).

A typical microturbine system is based on the Brayton cycle, and consists of a combustor, turbine, electricity generator, compressor, and recuperator. As a single unit the micro gas turbine suffers from limitations including low electricity efficiency, high capital cost and ambient temperature sensitivity (Ferrari 2017). These are mostly remedied by combine micro gas turbines with technology such as SOFC's to form CHP systems. Within a CHP system, micro gas turbines are used whereby the electricity produced alongside SOFC stack(s). The natural gas is mixed with the compressed air and combusted inside isobaric conditions (Gurrappa, I 2010), where the resulting gas is used to run the turbines. The exhaust gas exists there at very high temperatures (500-600 degrees Celsius), which is then heat recovered with hybrid systems; this kind of hybrid SOFC/mGT system can provide a thermal efficiency of greater than 70% (Rena 2019).

A major advantage of gas turbine technology is fuel tolerance and flexibility. Gas turbine systems can be adapted to use almost any flammable gas or light distillate petroleum products, including gasoline (petrol), diesel and kerosene (paraffin), all of which are readily accessible on market; of these, natural gas is the most commonly used fuel (Woodbank 2005). Other advantages of utilising micro gas turbines are the low emissions, parallel/modular systems to allow scaling up systems, flexible operation in terms of timing cycles that can complement other power source or load systems, small area requirement, high fuel tolerance where methane (CH_4) content can be as low as 30% (Ramadhani 2017). Further, micro gas systems have few moving parts which results in a low maintenance cost, and as a generation system, features a relatively high overall efficiency.

2.6 Hybrid SOFC/mGT Systems

2.6.1 Hybrid SOFC/mGT Systems Overview

There are several possible hybrid system opportunities with SOFC technology, which in general aim to utilize the energy content within the exhaust steam, as well as the electrical output of cell stacks, with the aim of maximizing plant energy efficiency (Ferrari 2017). Examples of these integrated, hybrid systems include steam power plants, combined cycles plant and gas turbine integration (Palsson 1999). The latter hybrid solution is the one that has the least development hurdles as do the steam and combined plants arising from issues in designing on a small-scale, as well as efficiency hurdles.

Energy optimisation within generation systems spurred Siemens Westinghouse to run a hybrid focussed on the development of tubular SOFC augmented to suit a turbine in order to utilise the heat by-product (Veyo 2002). The result of this was increasing the overall efficiency of the system and reducing the net cost of electricity without requiring additional fuel, and further combustion of fuel in the turbine. This achieved an efficiency of 70% (Hassmann 2001). Other industry bodies such as Rolls Royce and General Electric also developed an SOFC stack that combined with gas turbines for distributed generation purposes (Rolls Royce 2007) (General Electric 2015).

Microturbines have been shown amenable to integration with a high temperature fuel cell due to the well-matched temperature and pressure characteristics of an SOFC and microturbine in a hybrid system (Deng 2019). As such, current industry developments around SOFC plant involve micro gas turbines (mGT), known as the hybrid SOFC/mGT. Theoretically, SOFC/mGT systems qualify as the most efficient power plants based on fossil fuels (Ferrari 2017). Constructed as small-size power plants, these systems have significant distributed power generation uses. As a hybrid, SOFC/mGT systems are highly efficient – several studies have shown these system efficiencies competitive (Figure 6) to several other comparable technologies (Ferrari 2017).

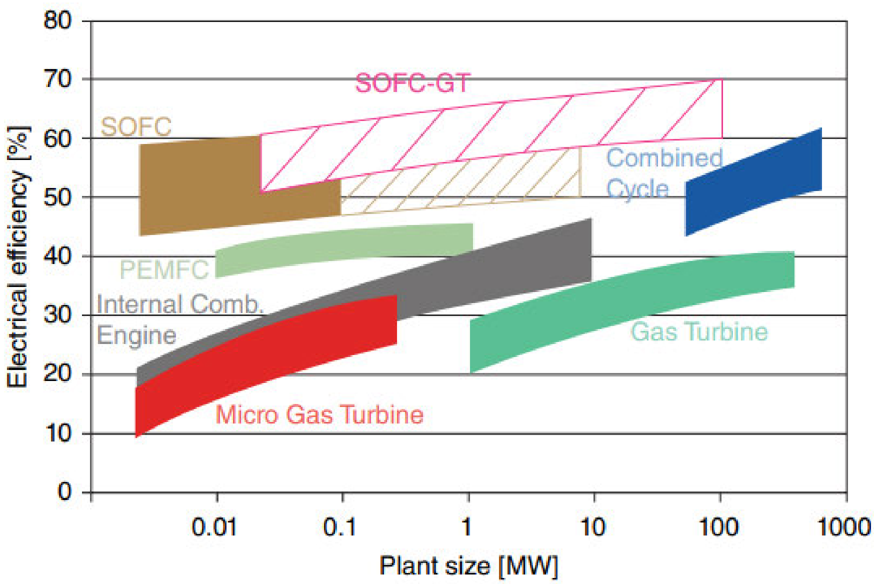

Figure 6: Electrical Efficiencies and Plant Size of Various Fossil Fuel Based Plant Types (Ferrari et al. 2017, P. 142)

2.6.2 Hybrid SOFC/mGT Systems – Physical Coupling

For an SOFC system coupled with a recuperated gas turbine (Figure 7) shows the coupling where the combustion chamber (air side) is connected to the fuel cell. The compressed air is fed into the SOFC stack (cathode side) downstream of the counterflow recuperator (air side). The anodic exhaust gas is mixed with the cathodic outlet flow in the off-gas burner located upstream of the expander. This exhaust gas is used on the hot side of the recuperator. Initial theoretical calculations for this design layout produced an electrical efficiency close to 82%, with approximately 69% of the electrical power produced by the fuel cell (Ferrari 2010). However, these results are considered optimistic as they do not account for realistic operational and design constraints such as fuel processing issues and other temperature constraints in design, such as the higher temperatures implying more expensive materials used in the recuperators (Ferrari 2017).

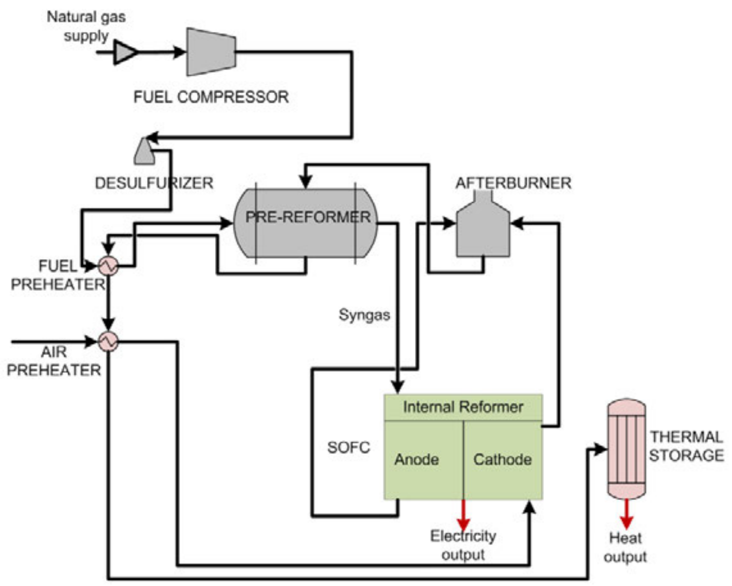

Figure 7: Generic Flow Diagram of an SOFC-based Combined Heat and Power (CHP) System (Arsalis, A 2019, P. 393)

2.6.3 Hybrid SOFC/mGT Systems – Thermal Coupling

The high operating temperatures of SOFC systems allow important cogenerative applications, including the possibility of harnessing the generation of both electricity and the superheated steam exhaust for other processes, such as water boiler/storage unit heating (Palsson 1999). SOFC/mGT systems rely on the coupling between the two technologies, with synergetic operational improvements regarding combined cycles to the utilization of the high temperature exhaust flow produced by the SOFC stack.

Micro gas turbines operate with similar mass flow values and pressure levels (atmospheric or pressurized between 4-7 bars) as existing SOFC stacks (Ferrari 2017). Additionally, the turbine inlet temperature (TIT) values for such systems are close to stack discharge conditions (Ferrari 2017). In order to increase the efficiency of the couple mGT/ SOFC hybrid, correct placement the off-gas burner (OGB) is vital (refer Figure 8). In the case of low-temperature SOFCs, this component has to be installed between the stack and the turbine (to have the correct TIT value), but for high-temperature stacks the OGB could be located in a recirculation line to pre-heat the cathodic inlet flow (Ferrari 2017).

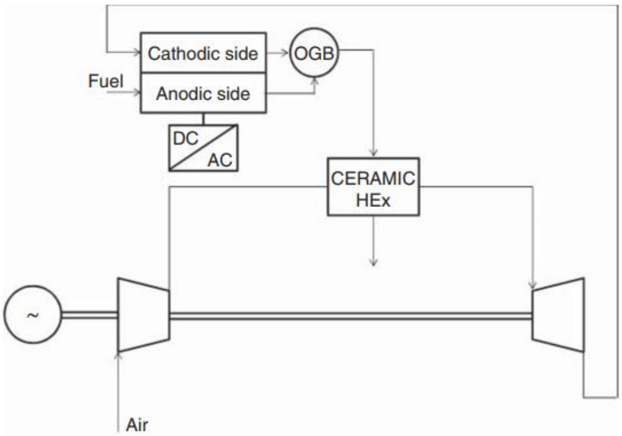

Figure 8: General Schematic of an Atmospheric SOFC/mGT Hybrid System (Ferrari et al. 2017, P. 50)

2.6.4 Hybrid SOFC/mGT Systems – Electrical Coupling

SOFC are one of the most efficient devices to convert fuel chemical energy directly to electrical energy with efficiency values in the 50-55% range (Ferrari 2017). These devices produce electrical energy in direct current (DC) form, and so it is necessary to employ power electronics to invert to 50/60Hz alternating current (AC) in order for the SOFC hybrid system to be useful to standard appliances and the grid. Additional to the obvious thermal coupling aspects to mGT/SOFC hybrid systems, there are electrical efficiency benefits. Specifically, since microturbines operate at high rotational speeds, a current rectifier is usually installed upstream of the inverter necessary to connect the machine with the electrical grid. A direct current line between the two power electronic systems allows a simpler connection with the SOFC electrical system that operates in the direct current mode (Ferrari 2010) if the stack is properly designed.

2.6.5 Hybrid SOFC/mGT Systems – Start-Up Process

The following excerpt was found in a journal article (Deng & Yang 2019, p. 5) and some wording was altered to summarise the start-up process of the SOFC/mGT system:

> "The start-up of the SOFC/mGT system is a complicated process. This is primarily due to differing levels of thermal inertia of the SOFC stack and the mGT equipment. To protect the SOFC stack, the start-up process of the SOFC and the mGT are initially separate (Deng & Yang 2019, p. 5). To begin the start-up, the mGT needs to be started with its rotation slowly approaching nominal speed. Once a fraction of nominal speed has been reached, the high temperature, high pressurized air of the heat exchanged outlet flows into the SOFC cathode to begin heating the SOFC (Deng & Yang 2019, p. 5). The acceleration of the mGT must be controlled to maintain a safe start-up range, while also being fast enough to be useful. Control equipment within the SOFC/mGT

optimizes the parameters involved in this start-up process. Once the heat exchanger has transitioned the thermal inertia of the system from cold state to hot state, the unit is started by the motor to gradually increase the speed of the compressor and turbine (Deng & Yang 2019, p. 5). After the initial purge phase of the compressor and turbine, the rotation speed of the gas turbine which is driven by the starter motor gradually increases; once reaching 20% nominal speed, the gas turbine ignites and the rotational speed increases to trip speed (60% nominal), at which point the driving source of the mGT switches from the starter motor to the turbine (Deng & Yang 2019, p. 5). After this point, the kinetic energy of the mGT is provided by the power of the turbine. The rotation speed of the gas turbine reaches the rated speed, and the SOFC stack prepares to be fully heated. After the rotational speed of the mGT reaches the nominal speed, the pressure rate of the compressor reaches the nominal speed, and the pressure rate of the compressor keeps a small range variety (Deng & Yang 2019, p. 6). The SOFC cathode valve gradually opens; meanwhile, a bypass valve closes to avoid compressor surge and ensures the air flow of the system is kept constant. In order to heat the SOFC to about 600°C, the outlet temperature of the turbine is then improved to 870°C, which is still in the safe operating temperature range for the turbine. The removes the need for any additional heating device. At 1700s from initial startup, the SOFC generates power by electrochemical reaction, at which point the SOFC system temperature is increased with the chemical reaction releasing heat. At close to 40 minutes from initial startup, the system start-up process has ended (Deng & Yang 2019, p. 5), and the system is running at full operating specification, outputting power to the connected load."

2.6.6 Commercialisation

In terms of commercialisation, there a number of technical issues in implementing SOFC/mGT hybrid technology. The first is the technological development for durability and affordability for commercial SOFC systems, which involves high production costs, meaning it would require high investment and the need for a significant push to produce scale that would enable competitive investor attraction. Commercialisation faces additional issues due to the high temperature operating conditions that leads to problems in designing external reforming componentry as part of the heat exchanger, piping and pumps, coupled with the historically higher cost natural fuels (Ferrari 2017). Higher operating temperatures required by SOFC's leads to component stress and hence life cycle reduction issues, as well as issues with system operation flexibility/timing. Also, due to market factors there are no commercially available gas turbines that have been specifically developed for SOFC applications; that is, no such twin technology (SOFC and mGT) systems optimised for the working cycles, pressure levels and generation capacities. While these are significant issues with SOFC systems and their hybrid variants, there are several companies that are commercialising these types of systems.

One of these companies is Delphi Corporation, which started to fabricate SOFC stacks for auxiliary power units (APU's) in order to supply on-board power while being engine-independent, featuring high efficiency and low emissions. These compactly designed units are 5kW-e, fuelled by gasoline and is a generally low mass system (short start-up times) (Ramadhani 2017). By using SOFC's within the APU, efficiency increased from 10-20% to 35% compared to the engine-connected power supply alternative (Ramadhani 2017). With the SOFC APU concept, there is no requirement to have complicated water management for the electrolyte, or compatibility in terms of temperature between the reformer and stack, as well as high tolerance of fuel impurities. This APU was designed to optimise the reformer in order to increase APU efficiency. Recycled exhaust from the anode is fed into the reformer within the API, where incoming hydrogen is used to improve fuel utilisation.

3.0 Methodology

3.1 Methodology Overview

The methodology aims to produce key outcomes that satisfies the aims and objectives of this final year project, that is, to demonstrate the utilisation of the SOFC/mGT system within practical use-cases. This is achieved by first evaluating advantages of the system, in order to assess and understand the value of the SOFC/mGT hybrid in cogeneration applications and in terms of environmental metrics. By comparing this hybrid system to other relevant competing distributed supply sources, key advantages such as energy efficiency, start-up time, time-of-use and emissions were demonstrated.

Once these advantages are evaluated, the methodology then considers factors that would affect utilization of the SOFC/mGT technology within specific use-cases. Site-specific load and supply factors are defined for the use-case, and the parameters of the proposed SOFC/mGT system are defined in terms of class and capacity for thermal and electrical power. These values for the hybrid system are then scaled for optimal system sizing. Finally, these load and supply factors are aggregated with the proposed integrated SOFC/mGT system to evaluate how effective the utilisation of the proposed system is within two specific use-cases: firstly, application to a multi-storey residential complex in an urban, cold climate environment. Secondly, application to a remote community hospital with export to a local feeder supplying mixed residential/commercial loads. The results of this methodology section are then summarised and discussed in Section 4.0.

3.2 Evaluating Advantages

3.2.1 Efficiency

The SOFC/mGT system has key advantages in energy efficiency. More specifically, these efficiency advantages are categorized in terms of both net electrical efficiencies and total thermal efficiencies. To highlight these advantages, comparison against other similar generating technologies were made, and then specifically against other conventional micro gas turbine systems to highlight the advantage of combining the turbomachinery with SOFC's.

In terms of conventional micro gas turbine efficiencies, Figure 9 shows efficiency values for several microturbine plant, ranging from 28% to 33%, specified in terms of 'LHV', which is a ratio of energy efficiency in terms of the fuel's low heating value (LHV).

Model	Manufacturers	Power Output	Set	Total Efficiency (LHV)	Pressure Ratio	TET	Nominal Speed
		kW		%		°C	Rpm
-	AlliedSignal	75	A Shaft	30 (HHV)	3.8	871	85,000
TA 45	Elliott Energy System	45	A Shaft	30	-	871	-
TA 80	Elliott Energy System	80	A Shaft	30	-	871	68,000
TA 200	Elliott Energy System	200	A Shaft	30	-	871	43,000
C30	Capstone	30	A Shaft	28		871	96,000
C65	Capstone	65	A Shaft	29		871	85,000
C200 HP	Capstone	200	A Shaft	33		870	45,000
-	Power Works^{TM}	70	Two Shafts	30 (HHV)	3	704	-
MT 100	ABB	100	A Shaft	30	4.5	950	70,000

Figure 9: Technical Characteristics of Leading Microturbine Manufacturers (Nascimento et al. 2013)

For comparison purposes, the Elliot Energy System TA200 (Nascimento et al. 2013) was selected (Figure 9) due to it having comparable power output values (250kW) as the MEGAMIE (Model 10) 250kW class SOFC/mGT hybrid system (Mitsubishi Heavy Industries 2015), in order to assess the efficiency benefits of the mGT plant combined with the SOFC as a hybrid system.

Due to the prototype/demonstration level of SOFC/mGT hybrid development, the modelling of the methodology was based on the proposed thermal and electrical supply of the MEGAMIE SOFC/mGT system. The MEGAMIE system (Model 10) is classed as a 250kW system, specified with a SOFC power output of 176.3kW-AC, and a mGT power output of 34.8kW-AC, resulting in a gross power output of 211.1kW-AC (Mitsubishi Heavy Industries 2015). The net electrical efficiency of a system with this class is 55% (Figure 10), however the total thermal energy reaches 73% efficiency when the thermal energy is recuperated/utilized within the system (output of hot water at 85°C). This meant a thermal capacity equivalent of 89.882kW-th. For modelling purposes, the thermal power equivalent was directed to an insulated boiler, which then was able to provide hot water to the residential units.

The following charts were used to demonstrate these comparable efficiency values visually:

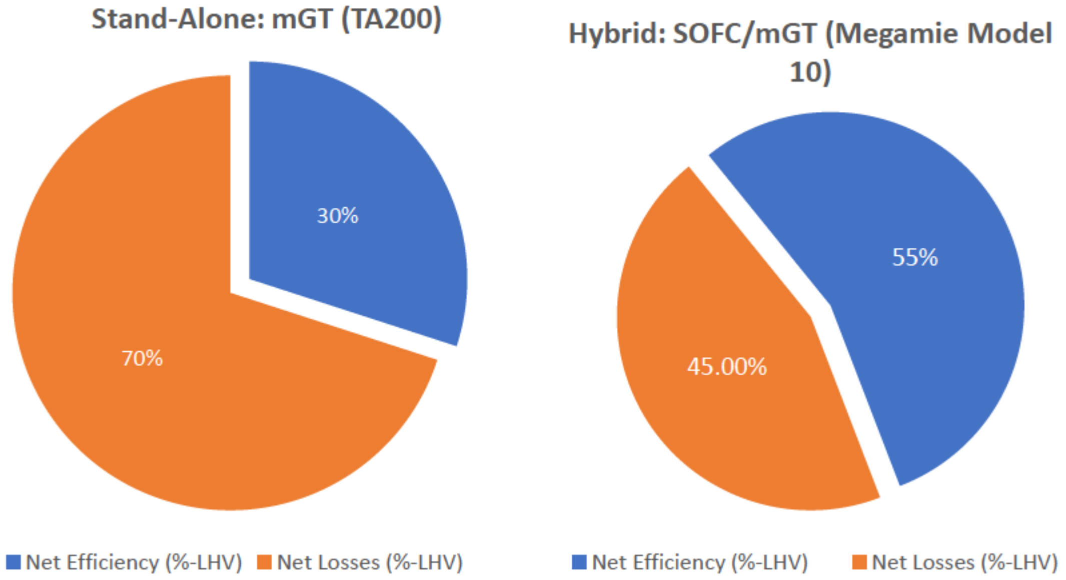

Figure 10: Electrical Efficiencies of Elliot Energy Systems TA200 (200kW) (LEFT) vs Megamie Model 10 (250kW) (RIGHT)

To offer evaluation in terms of the broader range of competing distributed generation systems, approximate efficiencies of various plant were collated (Figure 11) and charted (Figure 12).

PLANT TYPE:	APPROXIMATE TYPICAL PLANT SIZE (MW):	APPROXIMATE TYPICAL ELECTRICAL EFFICIENCY RANGE (%):	NOMINAL MID-RANGE PLANT EFFICIENCY (%):
Micro Gas Turbine (mGT)	0.025 – 1	15 – 30[1]	22.5
Gas Turbine (GT)	1 - 600	30 – 40[2]	35
Coal-Fired	100 - 2880[0]	30 – 40[3]	35
Combined Cycle (GT/Steam)	10 - 50	50 – 60[4]	55
Solid Oxide Fuel Cell (SOFC)	0.0015 – 0.25	50-55[5]	52.5

Solid Oxide Fuel Cell w/ Micro Gas Turbine (SOFC/mGT)	0.1 – 1	50-70[6]	60

[0] (Origin 2020); [1] (Kaparaju, P Rintala, J 2013); [2] (Bhatia, S 2014); ; [3](GE 2016); [4] (IPIECA 2020); [5] (Ferrari 2017); [6](Mitsubishi 2011).

Figure 11: Typical Sizing and Electrical Efficiencies of Various Generating Plant Types

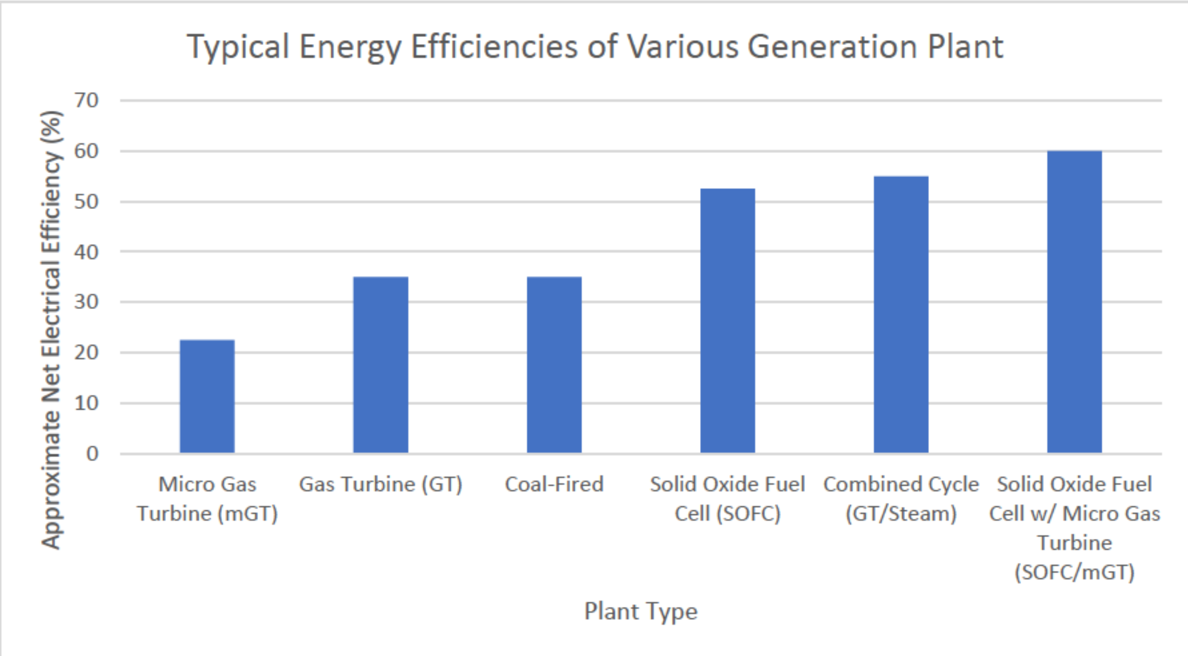

Figure 12: Typical Energy Efficiencies of Various Generation Plant Types

3.2.2 Start-Up Time

The SOFC/mGT system has another key advantage in fast start-up times relative to other rotating generator types. While this system is inherently slower than stand-alone large capacity (>1MW) gas turbine systems which can have start up time to full plant output of 2 minutes (Wartsila 2020), with other conventional gas turbine plant taking approximately 5/10 minutes, the SOFC/mGT is still competitive with other technologies with a 40 minute start-up time:

> *Furthermore, the dynamic behaviour of the start-up process have been investigated by starting up the hybrid system from atmospheric temperature. Studies on the start-up process, in which protecting SOFC and avoiding compressor surge are considered, shown that this system can be started in 40 minutes.* (Deng, K Yang, C 2019)

A visual example of applying this 40 minute start-up time of the SOFC/mGT system is plotted in Figure 13, showing the start-up of the system while the load increases above a nominal 50kW trigger, noting that output of power does not occur during the start-up period and only after this period has been completed.

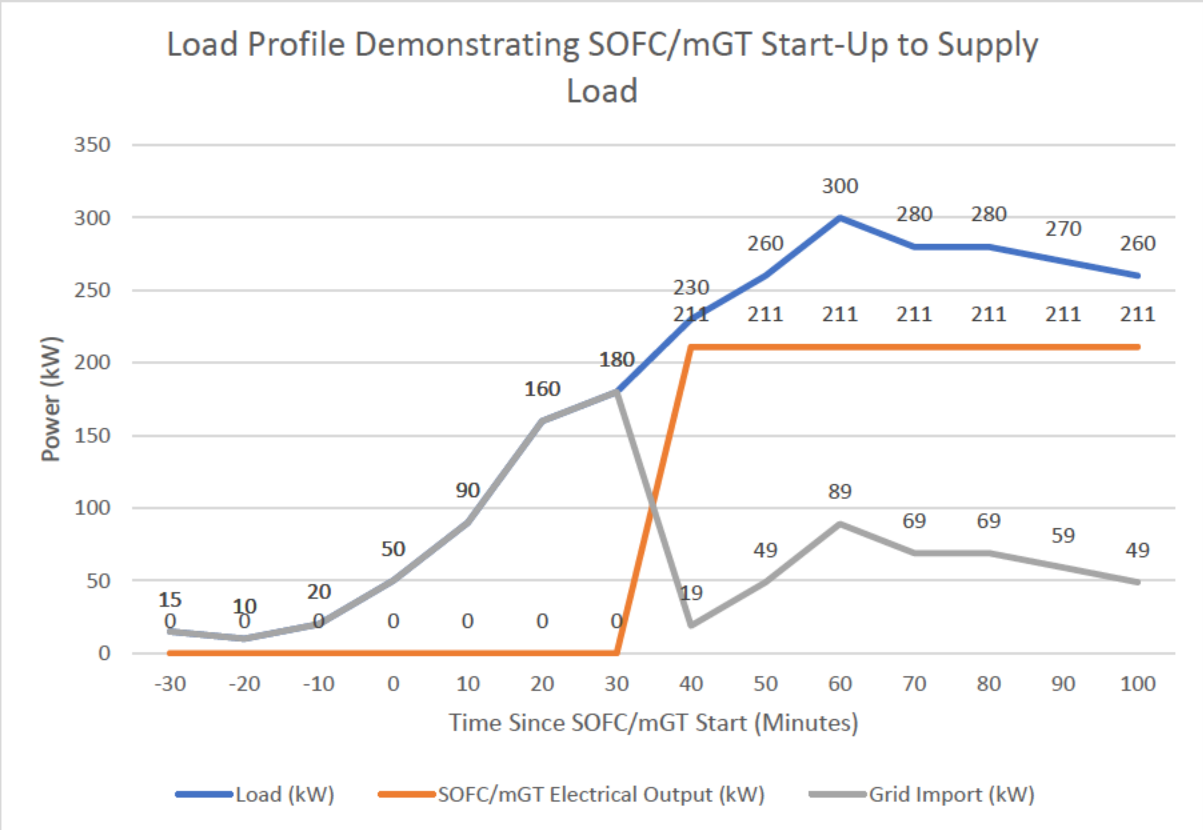

Figure 13: Example Of SOFC/mGT On-Demand Start-Up to Increased Loading

To draw comparison with other systems, start-up for conventional coal plant from time zero to output of full load capacity, Figure 14 shows coal fired plant using black coal with a hot start time of 1.5 hours and 12 hours for a cold start (Aurecon 2020). This highlights the key advantage of gas turbine systems within the distribution network, often fast enough to take advantage of high spot pricing (AEMO 2020) when other generators are not able to. These export pricing advantages are not considered in this methodology as the SOFC/mGT system is assessed in terms of local generation benefits.

Start types	Definition/ Shut down period	Start-up times	Start-up cost
Hot start	Less than 12 hours	1.5 hours (Black coal), 2 hours (Brown coal)	$298 / MW
Warm start	12 to 40 hours	3.5 hours	$379 / MW
Cold start	Above 40 hours	12 hours	$549 / MW

Figure 14: Coal-Fired Plant Start-up Times (Aurecon 2020)

Figure 15a below shows the start-up times of various generation plant, values in which were used to plot Figure 15b to demonstrate the key start-up time advantage of the SOFC/mGT system.

	SOFC/mGT	GT	Coal (Black)	Coal (Brown)
Start Time (Minutes)	40[1]	2-10[2]	90 (Hot Start) 210 (Warm Start)[3]	120 (Hot Start) 210 (Warm Start)[3]
Typical Plant Capacity (Range)	0.1 – 1 MW	1 – 600 (MW)	100 – 2880 MW[4]	100 – 2880MW [4]

[1](Deng, K Yang, C 2019) [2](Wartsila 2020) [3](Aurecon 2020) [4] (Origin 2020);

Figure 15a: Start-Up Times of Various Generation Plant

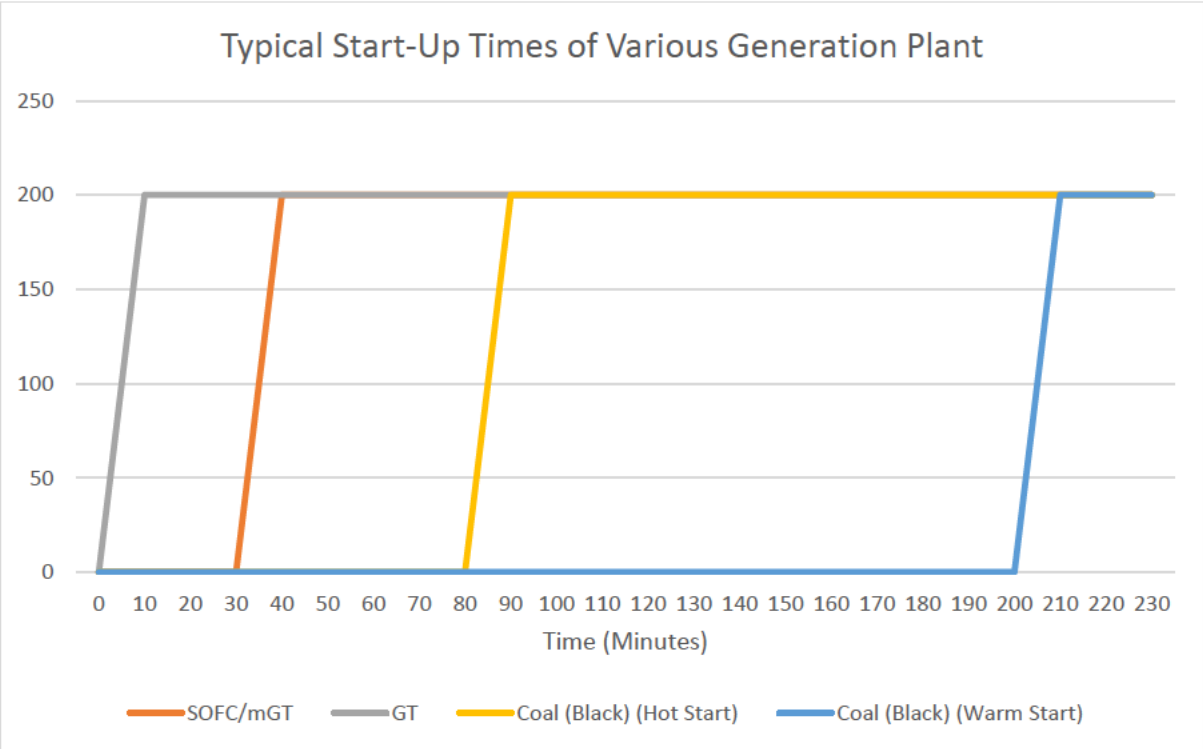

Figure 15b: Start-Up Times of Various Generation Plant

3.2.3 Time-of-Use

Another key advantage of the SOFC/mGT system is time-of-use. Being a generation system with a 40 minute start-up time as detailed in the previous section, the system allows a number of timing advantages to meet load demand. For comparison purposes, while not suffering any startup time, other sources of distributed generation such as embedded photovoltaic systems are restricted in terms of time of use with power generated during times of daylight only, as shown in Figure 16 for the typical power output of a 10kW solar system for reference. The

SOFC/mGT system can be used at any time of day, making it an ideal system to mix with distributed solar generator systems and other generation systems that are restricted in terms of start-up time or time of use.

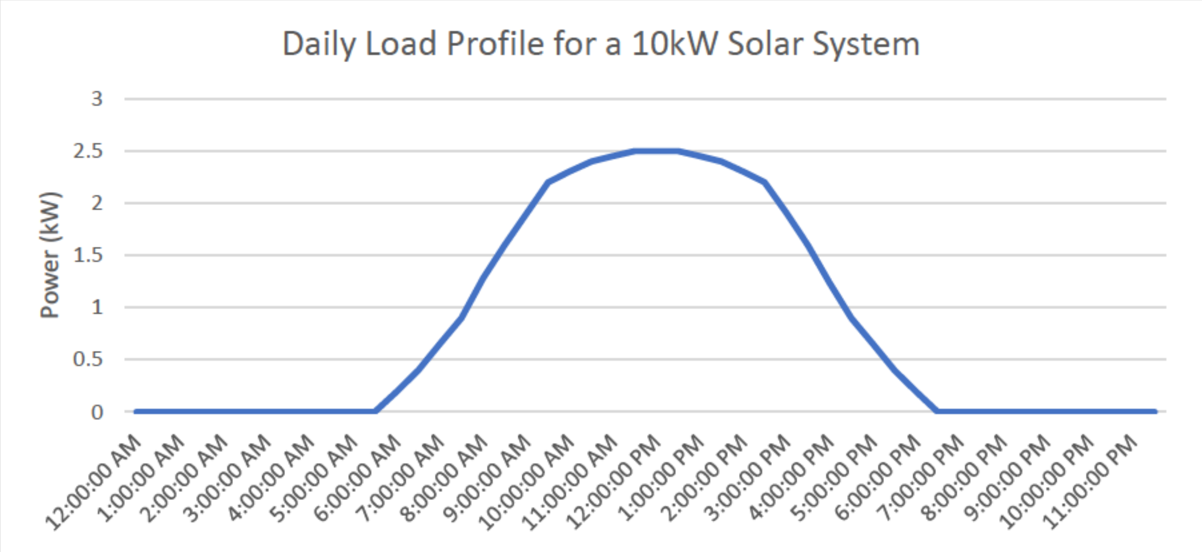

Figure 16: Daily Load Profile for a 10kW system netting 40kWh per day, assuming 6:30am sunrise, 6:30pm sunset, and no-cloud conditions.

3.2.4 Emissions

The SOFC/mGT system has key advantages in terms of emissions. To highlight these advantages, comparisons of carbon dioxide emissions of various fuel types were made against the gas fuels that the proposed SOFC/mGT would operate from:

	Emissions Factor (kg CO_2-e/GJ):		
Fuel Type:	**CO_2**	**CH_4**	**N_2O**
Dry Wood	0	0.1	1.2
Bagasse	0	0.2	1.2
Brown Coal (Lignite)	93.5	0.02	0.4
Sub-Bituminous Coal Bituminous Coal Hard Coal (Anthracite)	90	0.03	0.2

Natural Gas Liquified Natural Gas (LNG)	51.4	0.1	0.03
Liquified Petroleum Gas (LPG)	60.2	0.2	0.2
Gasoline	67.4	0.2	0.2
Kerosene (non-avtur[1])	68.9	0.0	0.2
Biodiesel	0.0	0.07	0.2
Crude Oil	69.6	0.1	0.2

[1] Avtur = Kerosene used for fuel in an aircraft

Figure 17: Typical Emissions Factors for Various Fuel Types (Australian Government 2017)

Figure 18 displays the tabulated values from Figure 17, demonstrating visually significantly less emissions resulting from operating on natural gas / LNG fuels.

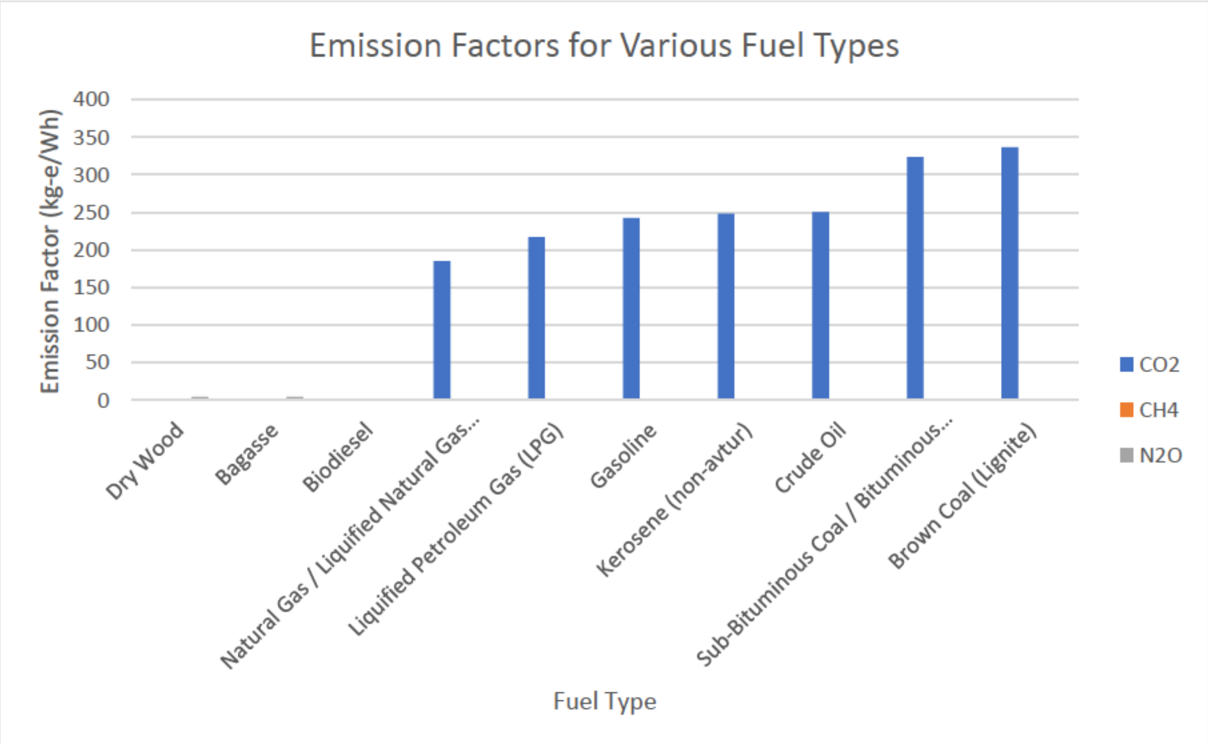

Figure 18: Emission Factors (CO2, CH4, N2O) for Various Fuels

Example: Calculations for Emissions for a 200kW (output) class plant.

$$Input\ Power = \frac{200\ kW}{55\%} = 364kW$$

Assuming a 24-hour operating cycle at full output capacity, for modelling purposes:

$$Energy\ Consumption = 364kW * 24h = 8.73MWh$$

Converting in terms of giga-joules (GJ):

$$Energy\ Consumption = 8.73MWh * 3.6\frac{GJ}{MWh} = 31.418\ GJ$$

Emissions Intensities for SOFC/mGT using natural gas:

For carbon dioxide CO_2 emissions:

$$Emissions\ Factor\ (CO_2) = 51.4\ kg\ CO_2 - e/GJ$$

$$Emissions\ Intensity\ (CO_2) = 31.418\ *\ 51.4 = 1614.895\ kg\ CO_2$$

$$Emissions\ Intensity\ (CO_2) = 1.6\ tonnes\ of\ CO_2$$

For methane CH_4 emissions:

$$Emissions\ Factor\ (CH_4) = 0.1\ kg\ CH_4 - e/GJ$$

$$Emissions\ Intensity\ (CH_4) = 31.418\ *\ 0.1 = 3.142\ kg\ CH_4$$

For nitrous oxide N_2O emissions:

$$Emissions\ Factor\ (N_2O) = 0.03\ kg\ N_2O - e/GJ$$

$$Emissions\ Intensity\ (N_2O) = 31.418\ *\ 0.03 = 0.9425\ kg\ N_2O$$

These calculations were made for various plant and fuel types, and collated in Figure 19 as follows:

Plant Type	**Plant Efficiency**	**Fuel Type**	**Fuel Emissions Factor (kg CO2-e/GJ):**			**Fuel Emissions Quantity (kg)**		
			CO2	**CH_4**	**NO2**	**CO2**	**CH_4**	**NO2**
Micro Gas Turbine	0.225	Natural Gas	51.4	0.1	0.03	3948	7.68	2.304
Coal-Fired	0.35	Black Coal	90	0.03	0.2	4443	1.481	9.8743
Coal-Fired	0.35	Brown Coal	93.5	0.02	0.4	4616	0.9874	19.749
Gas Turbine	0.35	Natural Gas	51.4	0.1	0.03	2537.7	4.9371	1.4811
GT Combined Cycle	55%	Natural Gas	51.4	0.1	0.03	1614.9	3.1418	0.9425
SOFC Unit	0.525	Natural Gas	51.4	0.1	0.03	1691.8	3.2914	0.9874
SOFC/mGT	0.55	Natural Gas	51.4	0.1	0.03	1614.8	3.1418	0.9425

Figure 19: Calculated Overall Emission for Various Fuels and Plant Types

For modelling purposes, several assumptions were made:

Assumptions: 200kW is within the generation capacity of all plant types.

Operating at full output capacity for 24 hours.

The values in the table above were charted to demonstrate the emissions of various plant in Figures 20, 21, 22.

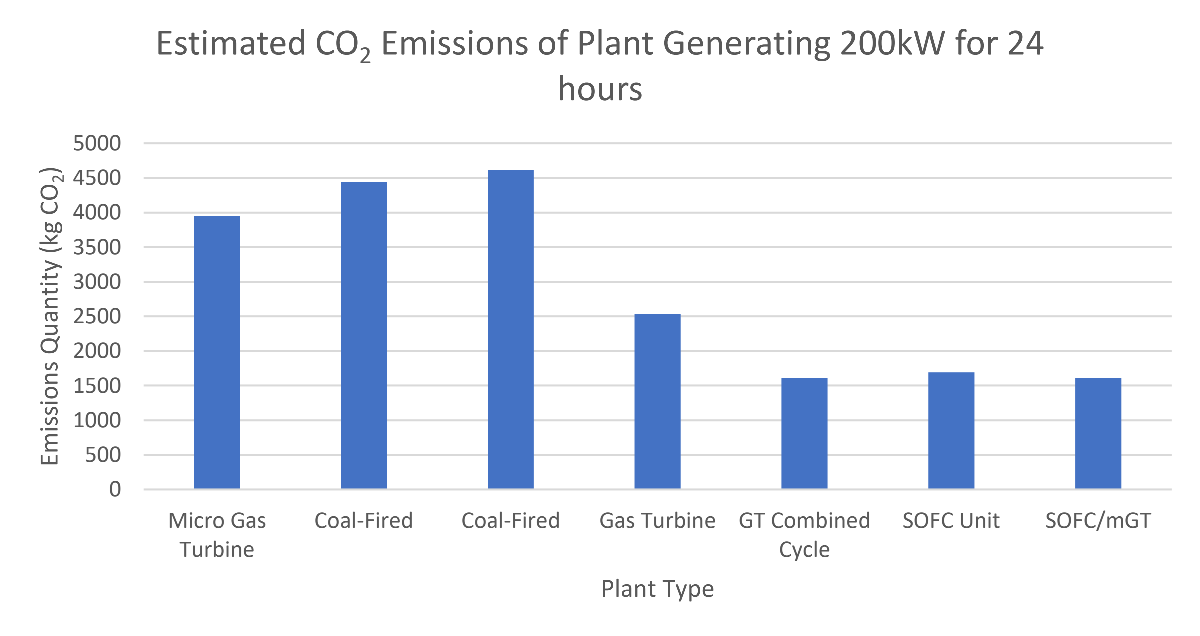

Figure 20: Estimated Emissions of Various Plant Types (CO2)

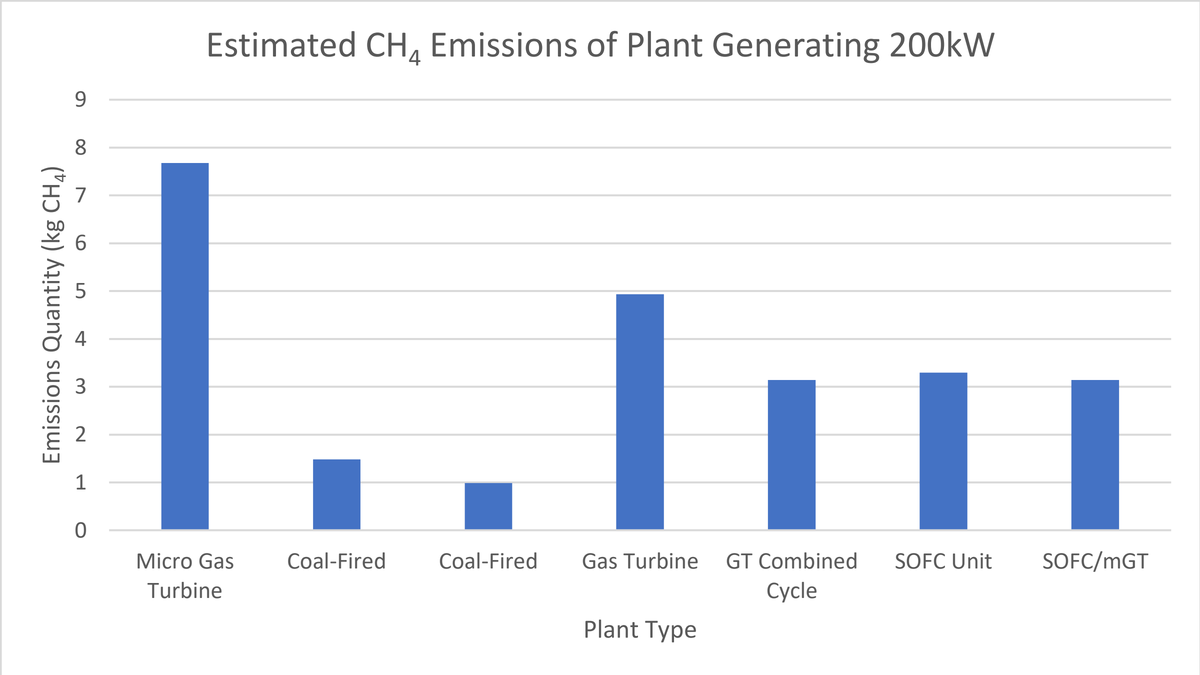

Figure 21: Estimated Emissions of Various Plant Types (CH4)

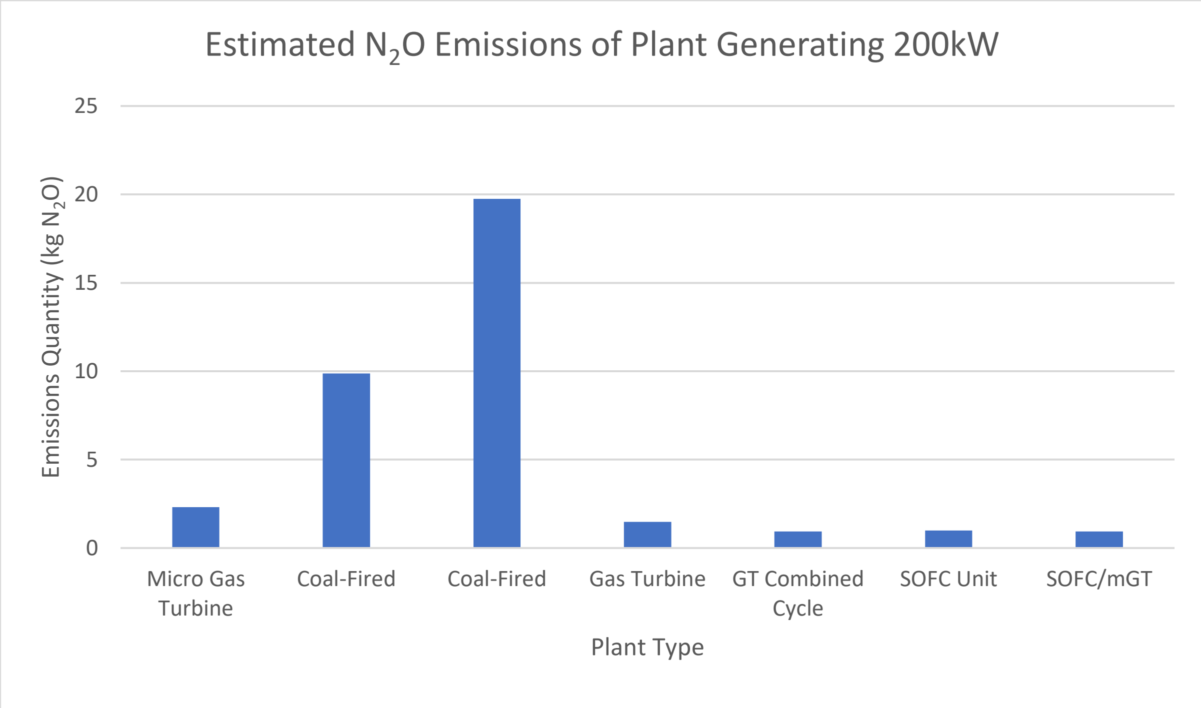

Figure 22: Estimated Emissions of Various Plant Types (N2O)

3.3 Use Case Application Overview

This section of the methodology addresses the aims and objectives of this paper in order to demonstrate utilisation of the SOFC/mGT system. This is achieved by first considering site-specific load factors to which the proposed system would be connected. Secondly, site-specific supply factors are considered to evaluate the effectiveness of the SOFC/mGT system for cogeneration and energy export purposes. Thirdly, the proposed SOFC/mGT system is detailed in terms of class and capacity, and later scaled for optimal system sizing. Finally, these load and supply factors are defined for proposed sites and are aggregated with the proposed integrated SOFC/mGT system to assess how effective the utilisation of the proposed system is within specific use-cases.

3.3.1 Load Factors

For the purposes of this methodology, these load factors are amalgamated into a blanket load category because in terms of household load profiles, these loads form the daily load profiles of the site which will be required to evaluate the proposed system. For this reasons, two load profiles are considered in this section: electrical loads and thermal loads. Electrical loads include all typical electrical equipment found installed on a property such as lighting, general power, motors and HVAC equipment. Thermal load profiles consistent of power usage for hot water systems, as the integration of the SOFC/mGT system is proposed via recuperated heat transferred directly to a boiler, the conceptual design of which is detailed in section 3.3.3. This level of approach was appropriate for the system data that was available from the demonstration SOFC/mGT system used to model the supply to these use-cases.

In order to generalise and understand what form the daily load profile that the average household takes, data was gathered from Ergon Energy (Ergon 2020) at the distribution level.

By looking at the daily load profile of a typical residential feeder, it is possible to assume daily load profiles at the household level once scaled down to typical energy consumption values. For this section, the daily energy usage of the average household was approximated at 16kWh, in line with sources of data referred to in section 2.1. In order to represent an average typical household load profile, four diverse, typical daily load profiles (Figures 23, 24, 25 26) representing of a household of four residents used:

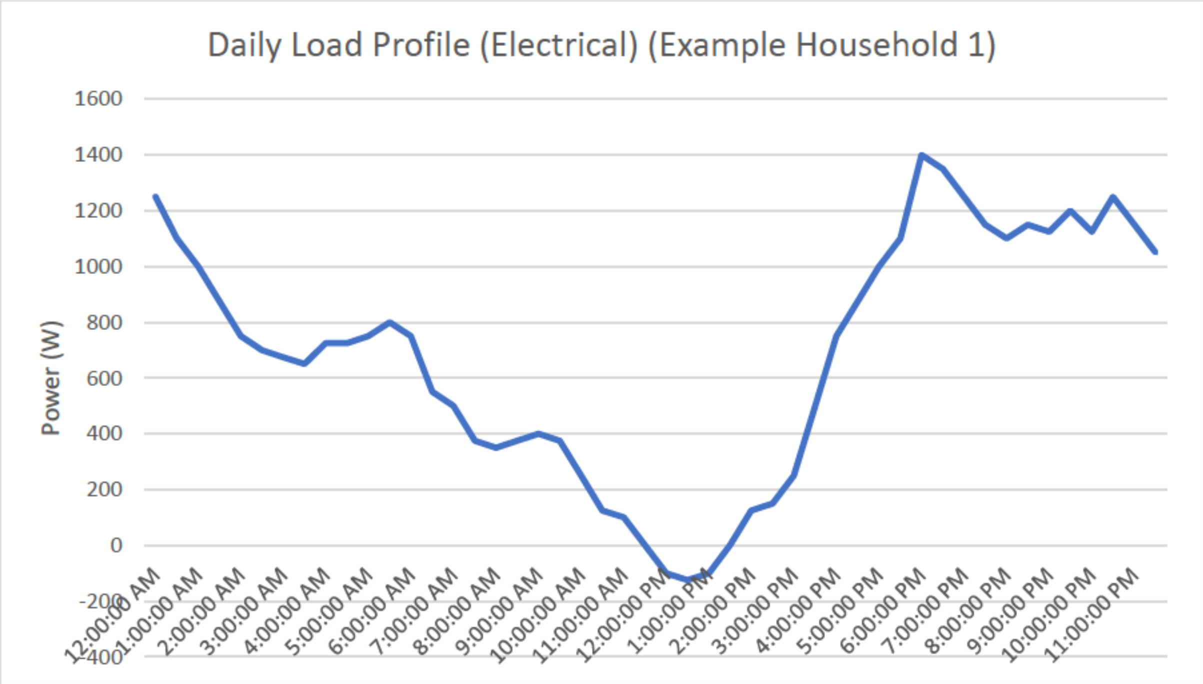

Figure 23: Daily Load Profile of a Typical Household (Example 1)

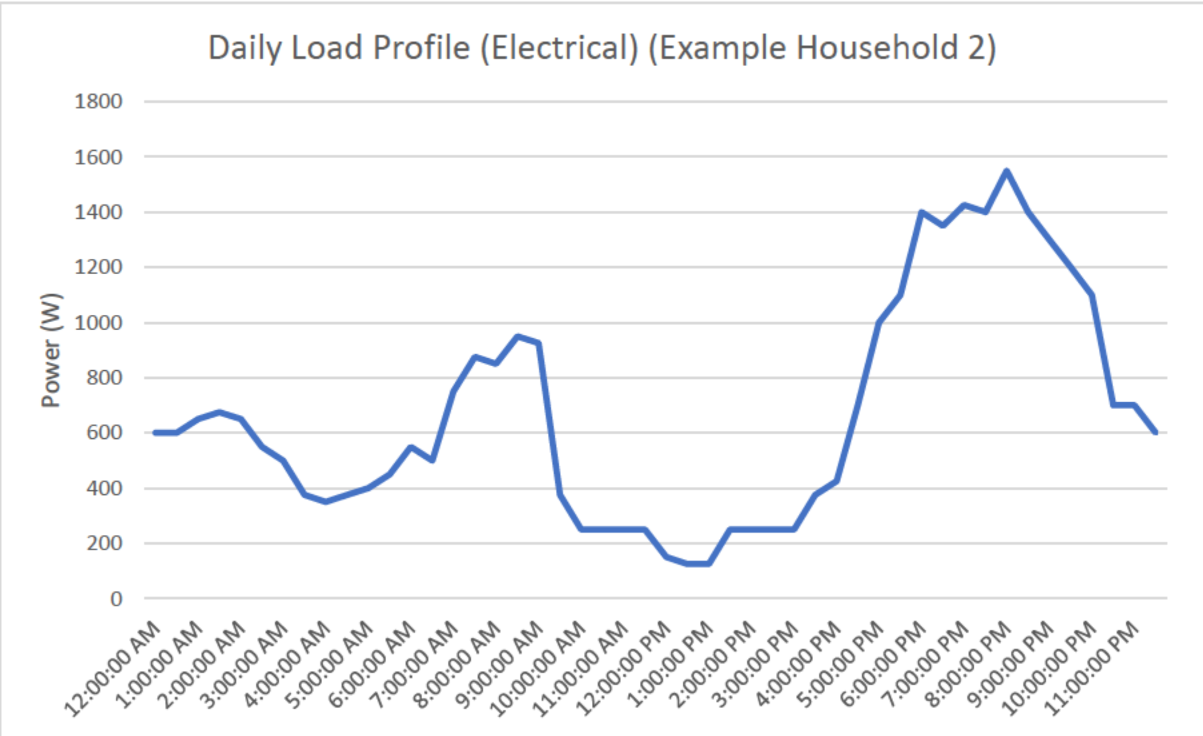

Figure 24: Daily Load Profile of a Typical Household (Example 2)

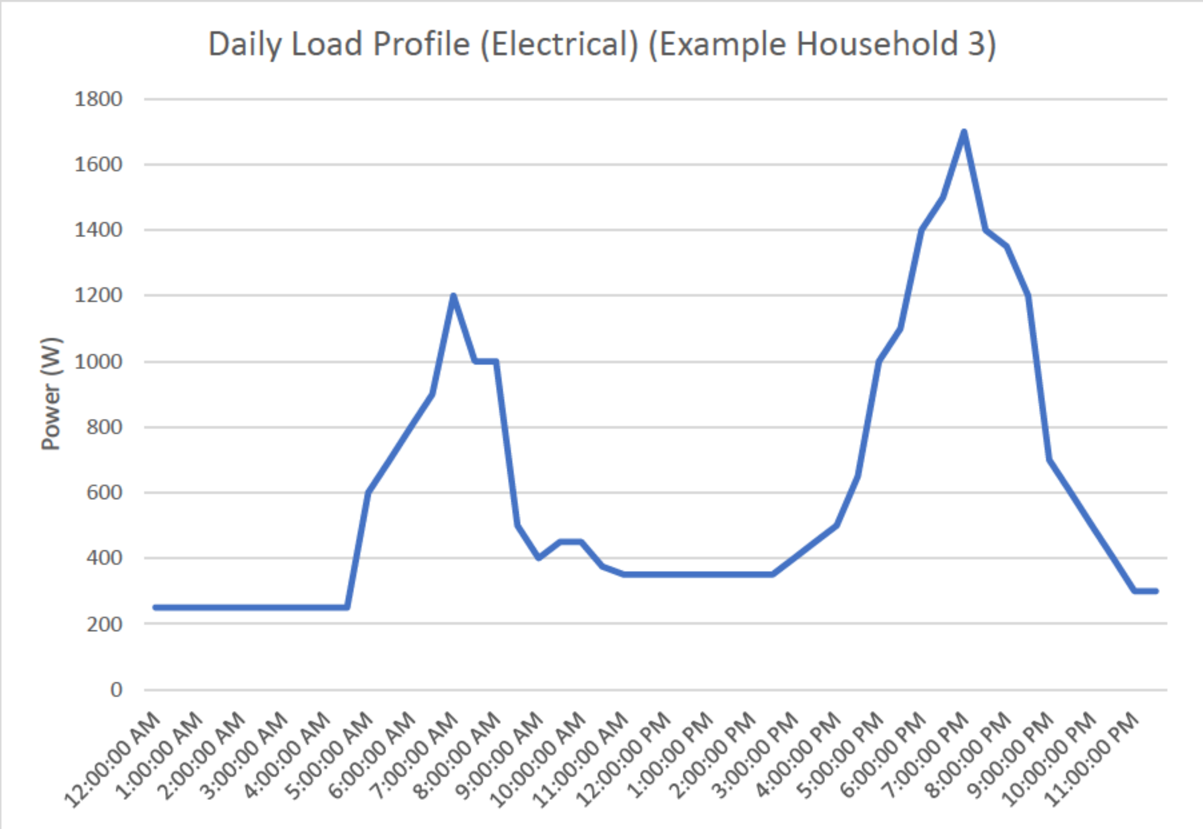

Figure 25: Daily Load Profile of a Typical Household (Example 3)

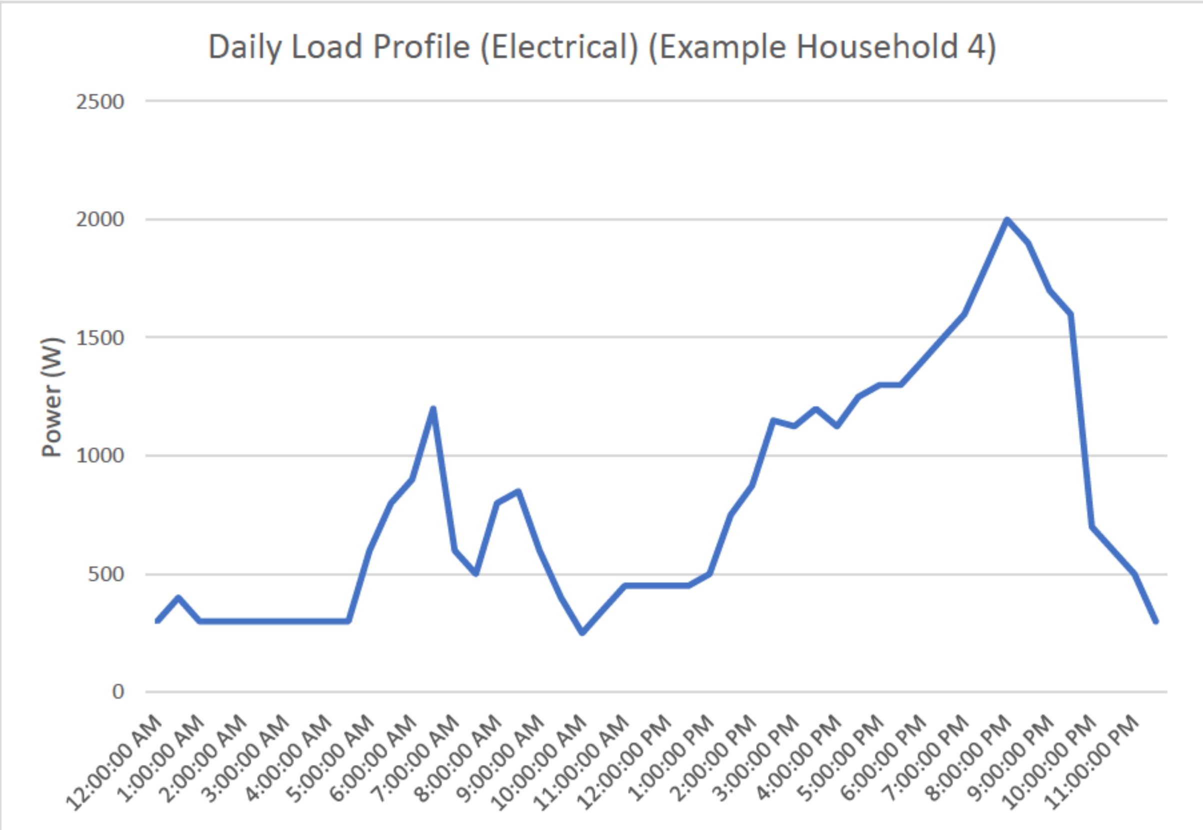

Figure 26: Daily Load Profile of a Typical Household (Example 4)

In terms of thermal load profiles, it is sufficient to gather typical hot water usage details on a per household basis. These values can then be scaled to suit site-specific parameters, such as number of residents, in order to estimate the usage of hot water within a site. For commercial sites, the estimate of typical hot water will have a predictable baseload with usage peaks at differing times depending on the site. For a typical household, the energy usage per day for a 2400W hot water system will be modelled from approximately 25.92MJ (7.2kWh-th) daily. For the purposes of this methodology, hot water systems of the storage type are considered and modelled within each use-case as this type of hot water system will emulate the boiler system as detailed in section 3.2.3 for the proposed SOFC/mGT system.

In order to represent typical energy usage for two different electrical load profiles for thermal demand were modelled in Figures 27, 28 and 29 as follows:

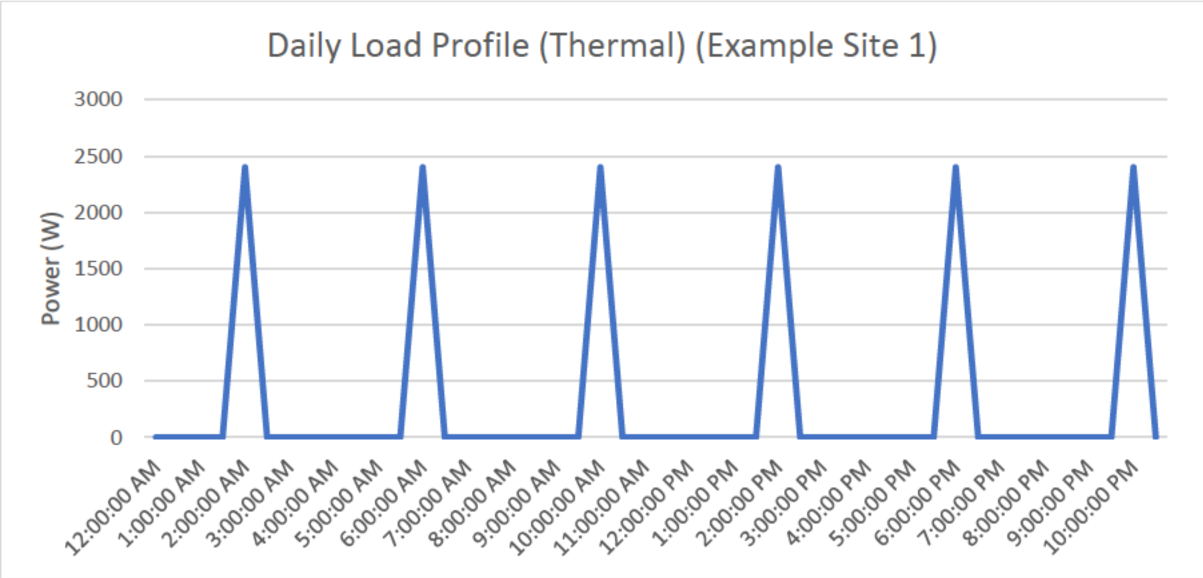

Figure 27: Example of Cyclic Timing Schedule for Thermal Load Supply, Example 1

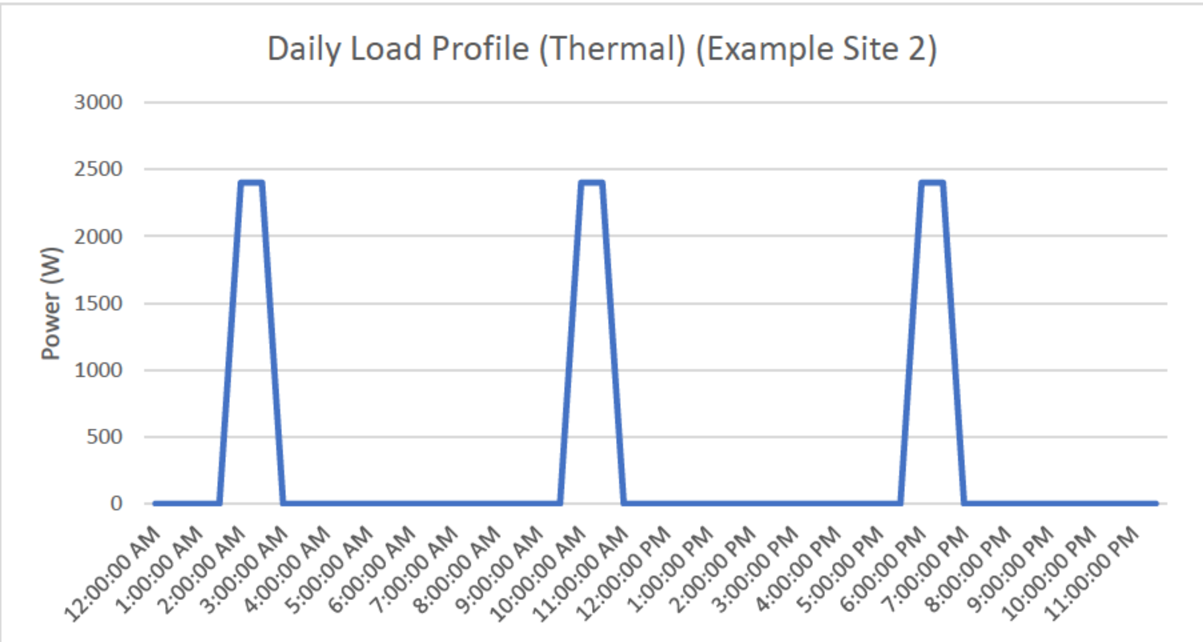

Figure 28: Example of Cyclic Timing Schedule for Thermal Load Supply, Example 2

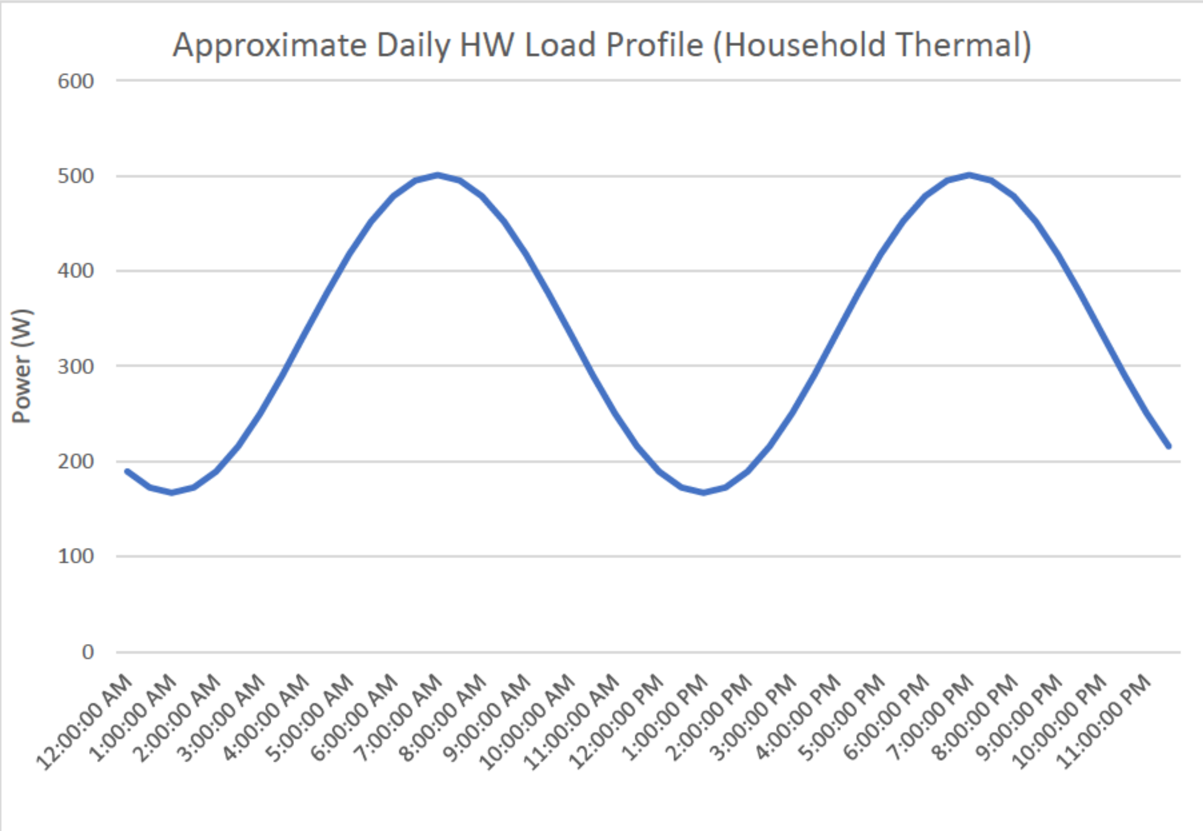

Figure 29: Approximate Thermal Load of Household, Cyclic Loading, with peaks during high-occupancy time of day

3.3.2 Supply Factors

Site-specific supply factors are also considered for evaluating SOFC/mGT system effectiveness. The first supply factor was the availability of a hydrogen rich gas supply at site, either via mains gas lines or storage tank. The availability of gas supply is fundamental to the SOFC/mGT system, so assumptions are made within subsequent modelling and analysis that gas supply pressure and capacity is adequate. For the case of the remote community, the gas mains were assumed to as sufficiently sized gas tanks and pressure available in the lines Secondly, the availability of electrical grid connection is assumed as it is required for purposes of cogeneration and energy export. The methodology assumed there was no export cap for the purposes of modelling. Gas mains and electrical grid connection on-site also allows cost comparisons to be made between the proposed SOFC/mGT generation system and grid costs per energy unit.

3.3.3 Specifying the SOFC/mGT system

Modelling of the integration of the SOFC/mGT hybrid system in the context of the use-cases detailed in section 3.3.4 is based on the Megamie SOFC/mGT system (Mitsubishi Heavy Industries 2015). This system was selected from limited hybrid systems due to the prototype/demonstration development stage this technology is currently in and selected on it being of a capacity useful for modelling purposes. The MEGAMIE system (Model 15) is classed as a 200kW system, specified with a SOFC power output of 176.3kW-AC, and a mGT power output of 34.8kW-AC, resulting in a gross power output of 211.1kW-AC (Mitsubishi

2020). In performance tests, this system accepts 339.8kW-th input for the SOFC equipment and outputs 176.3kW-AC boasting a net electrical efficiency (LHV) of 52.1% from actual performance test results (Figure 30). However, the total net energy efficiency reaches 73% (at 85°C hot water) when the thermal energy is utilized. This meant a thermal capacity equivalent of 89.882kW-th for the 200kW system. For modelling purposes, the thermal power equivalent was directed to an insulated boiler, which then was able to provide hot water to the residential units.

LOAD AND SUPPLY FACTORS SUMMARY **SYSTEM: SOFC/mGT 200kW Class**	
Parameter	Power Capacity
SOFC Fuel Heat Input	339.8 kW-th
MGT Fuel Heat Input	51.5 kW-th
SOFC Power Output	176.3 kW-AC
MGT Power Output	34.8 kW-AC
Auxiliary Power (System)	7.2 kW-AC
Net Power Efficiency (%, LHV)	52.1%
Total Energy Efficiency (%, LHV)	73% (85°C Hot Water)
SOFC/mGT Thermal Output	846.552 MBtu (IT)/hour = 248.1kW-th

Figure 30: Performance Results for the MEGAMI 200kW class SOFC/mGT system (Mitsubishi 2020)

3.4 Application to Use-Cases

This section of the methodology defines two use-cases in which the SOFC/mGT system specified in section 3.3.3 could be integrated.

3.4.1 Use Case 1

For use-case 1, integration of the SOFC/mGT system is modelled in the context of supplying a multi-storey residential complex. In this use-case, the multi-storey complex is comprised of 30 storeys with 5 units per floor, with an average of 4 persons per unit. The SOFC/mGT system would be fed via gas mains and located on the ground floor level of the complex, with its low voltage output fed into the main switchboard. In order to understand the effective utilisation of the proposed SOFC/mGT, it was necessary to model the load of the complex. For the modelling of this use-case, an assumption is that the average daily load profile for representing the typical household (Figure 31) is produced from the aggregated four Example Household Load Profiles in Section 3.3.1, and scaled to the number of dwellings in the complex (refer Figure 32), and that the complex is at 100% utilisation to model the worst-case load profile.

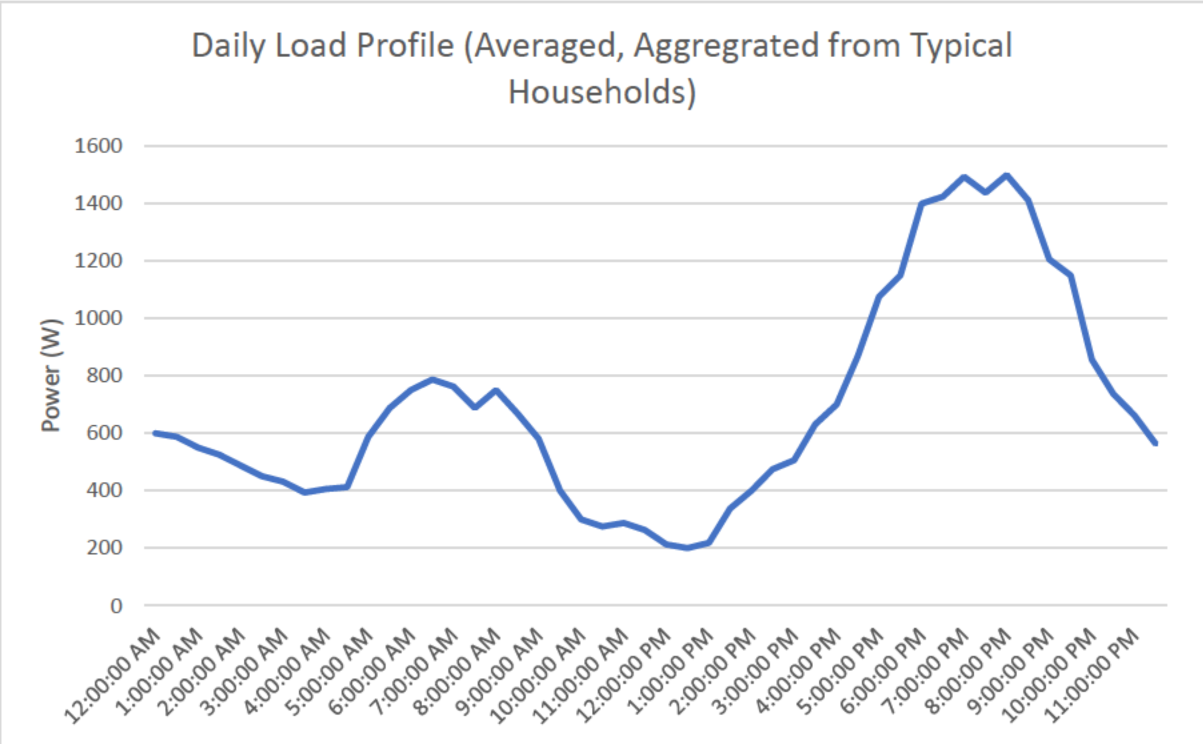

Figure 31: Aggregated, Average Daily Load Profile of a Single Household

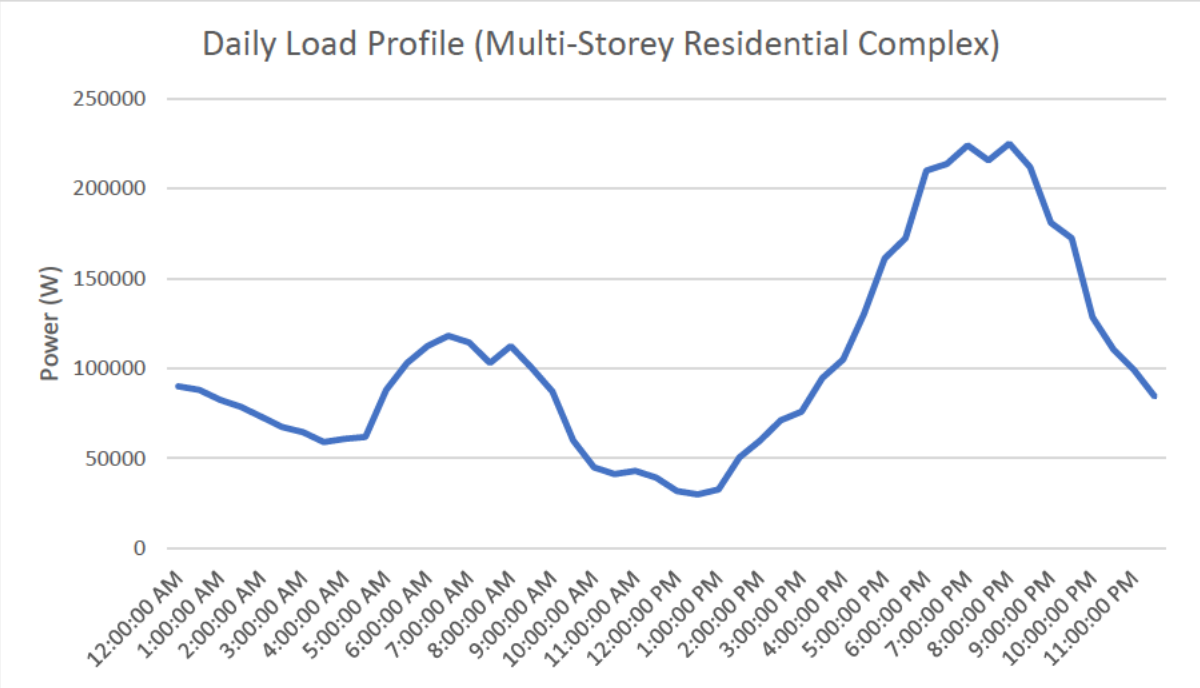

Figure 32: Multi-Storey Residential Complex Daily Load Profile

Supply Factors

Site-specific supply factors are also considered for evaluating SOFC/mGT system effectiveness. The following assumptions were made for the use-case regarding supply. Firstly, the SOFC/mGT system would be fed via mains of natural gas and located on the ground floor level of the complex. The availability of gas supply is fundamental to the SOFC/mGT system, so assumptions are made within subsequent modelling and analysis that gas supply pressure and capacity is adequate. Secondly the low voltage output fed into the main switchboard. Finally, that connection to import and export to the electrical grid is possible.

SOFC/mGT System

To suit the power demand required, the SOFC/mGT system specified (Section 3.3.3) is scaled by half, meaning that a 100kW class hybrid was used to suit the daily load profile of this use-case. Both electrical and thermal loads were considered; the thermal power equivalent (~44kW-th) produced by the SOFC/mGT system (Figure 33) was directed to an insulated boiler, which then was able to provide hot water to the residential units.

LOAD AND SUPPLY FACTORS SUMMARY **USE-CASE 1: SOFC/mGT 100kW Class**	
Parameter	Power Capacity
SOFC Fuel Heat Input	169.9 kW-th

MGT Fuel Heat Input	25.8 kW-th
SOFC Power Output	88.2 kW-AC
MGT Power Output	17.4 kW-AC
Auxiliary Power (System)	3.6 kW-AC
Net Power Efficiency (%, LHV)	52.1%
Total Energy Efficiency (%, LHV)	73% (85°C Hot Water)
SOFC/mGT Thermal Output	423.276 MBtu (IT)/hour = 124.03 kW-th

Figure 33: Performance Results for the MEGAMI 200kW class SOFC/mGT system, scaled to 100kW for use-case application (Mitsubishi 2020)

Integration

Integration of SOFC/mGT system in terms of supplying daily energy demand with three different methods. Three timing strategies to optimise utilisation of use case: always-on (Figure 34), load-trailing (Figure 35), threshold-triggered (Figure 36), as follows:

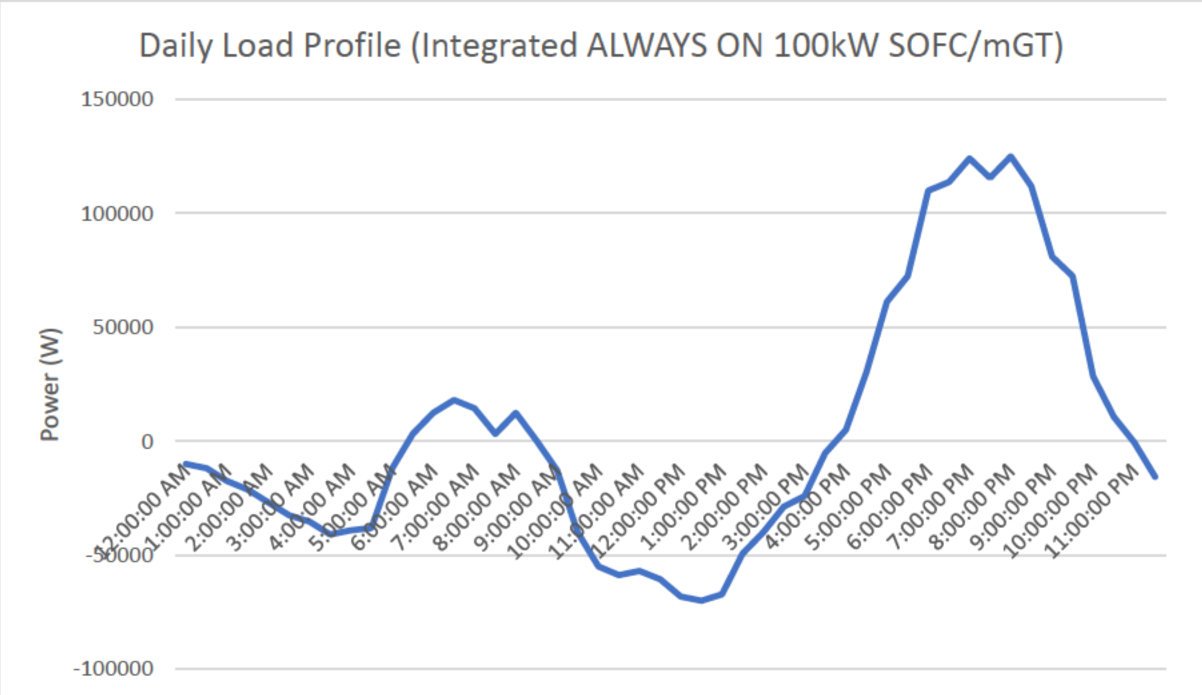

Figure 34: Daily Load Profile (Integrated SOFC/mGT with ALWAYS ON timing

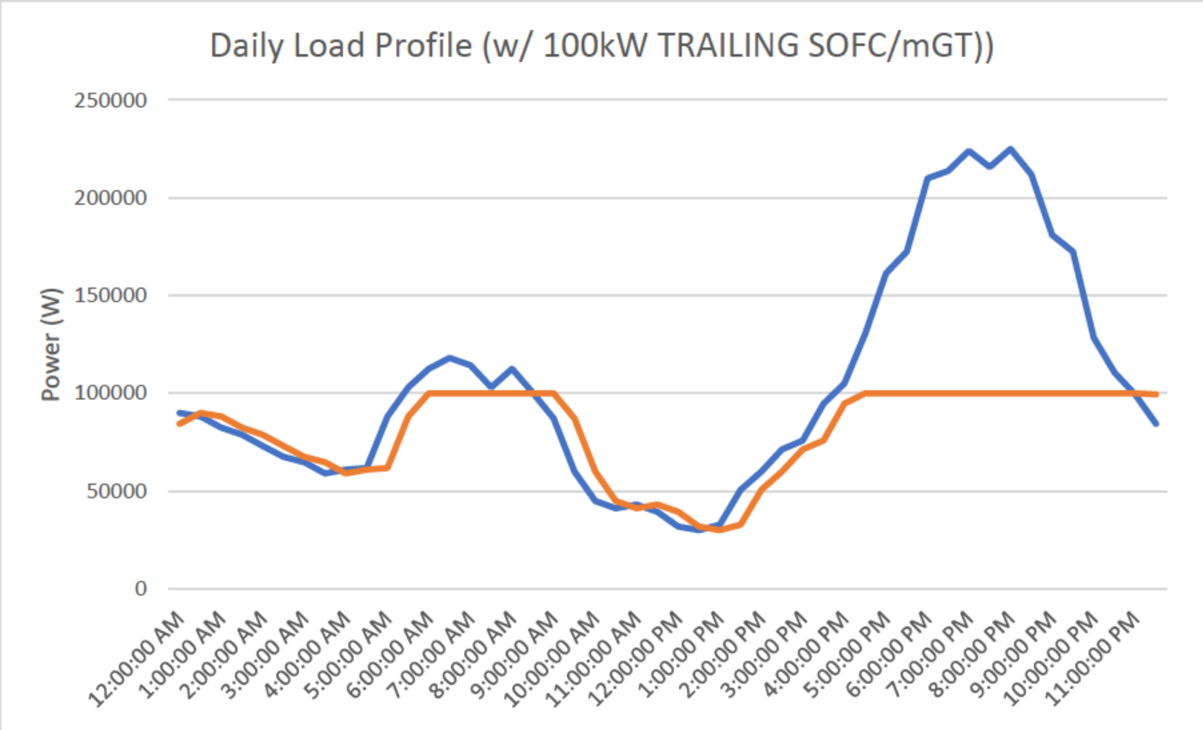

Figure 35: Daily Load Profile (Integrated SOFC/mGT with TRAILING timing

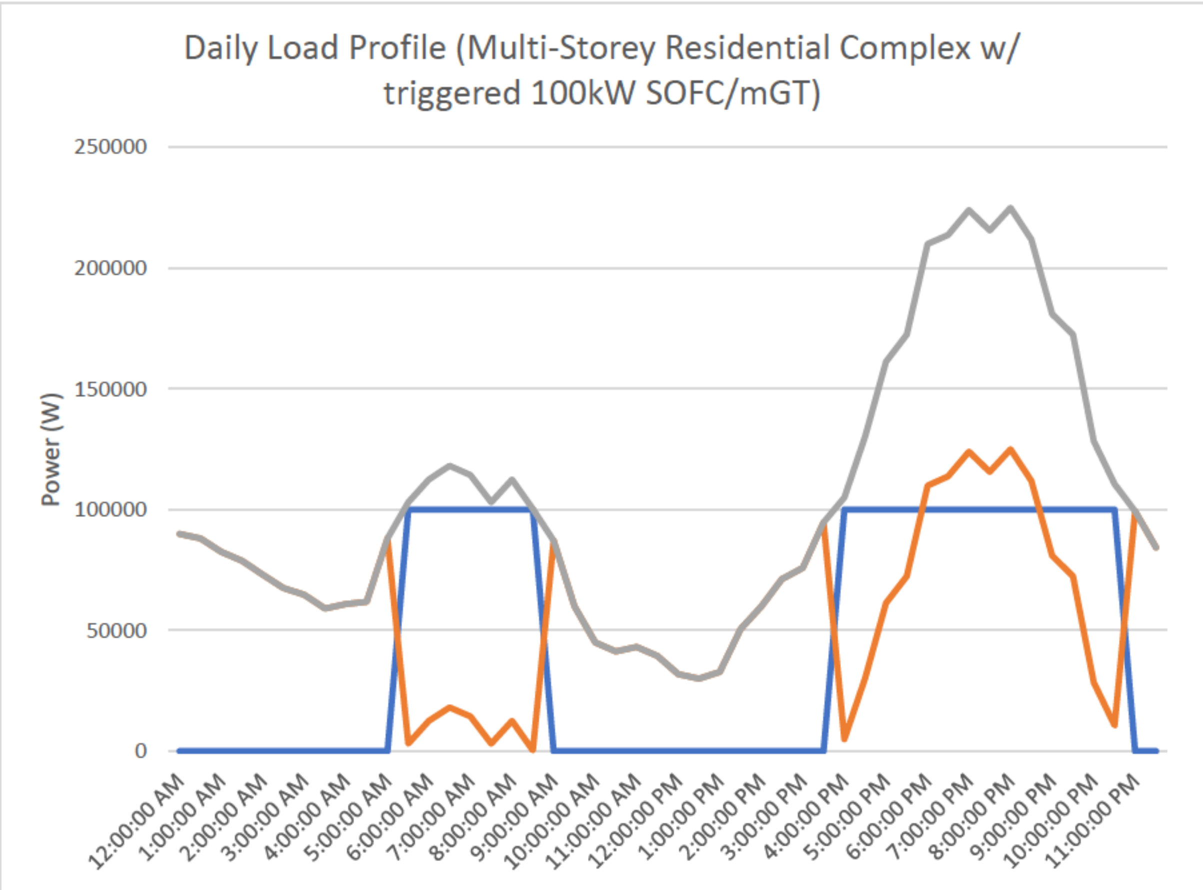

Figure 36: Daily Load Profile (Integrated SOFC/mGT with TRIGGERED ON timing

Thermal Energy Load

For use-case 1, the thermal energy demand of was modelled with an assumed 50% loss in energy from output of the SOFC/mGT system to use by the resident, resulting in 62kW-th from that specified in Figure 33. The following figures were formed to model typical household thermal demand (Figure 37), approximate residential complex demand (Figure 38) and the resultant thermal demand (Figure 39). Figure 40 was combined the electrical, thermal loads, with the SOFC/mGT supply with a triggered timing configuration (100kW-e).

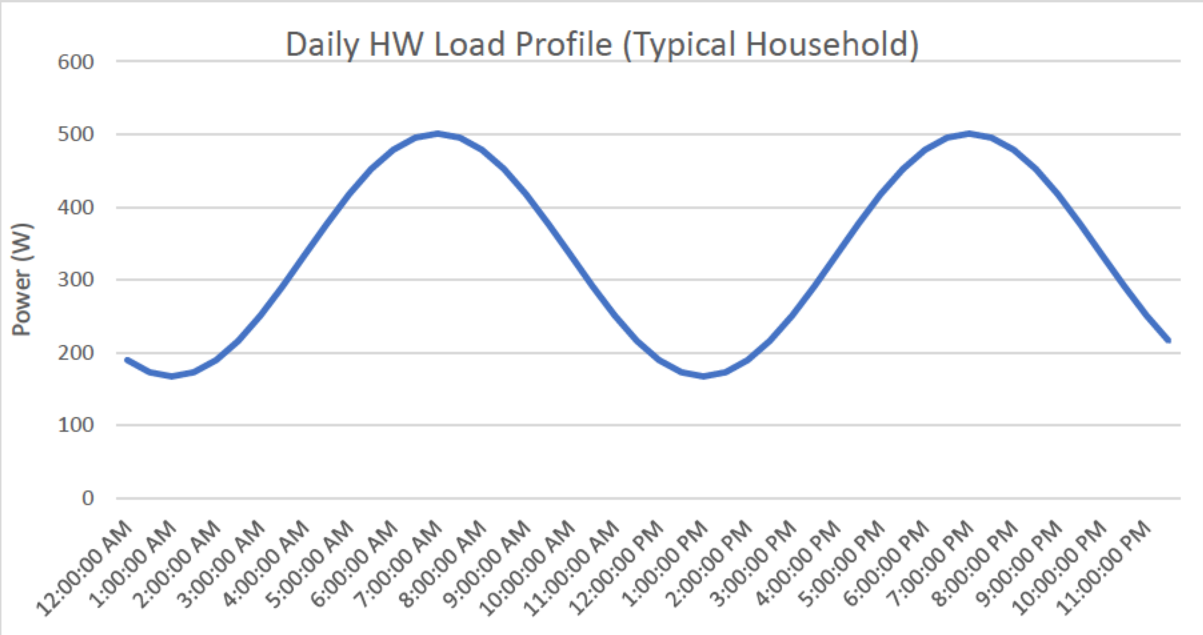

Figure 37: Daily Cyclic Demand Load Profile for a Typical Household

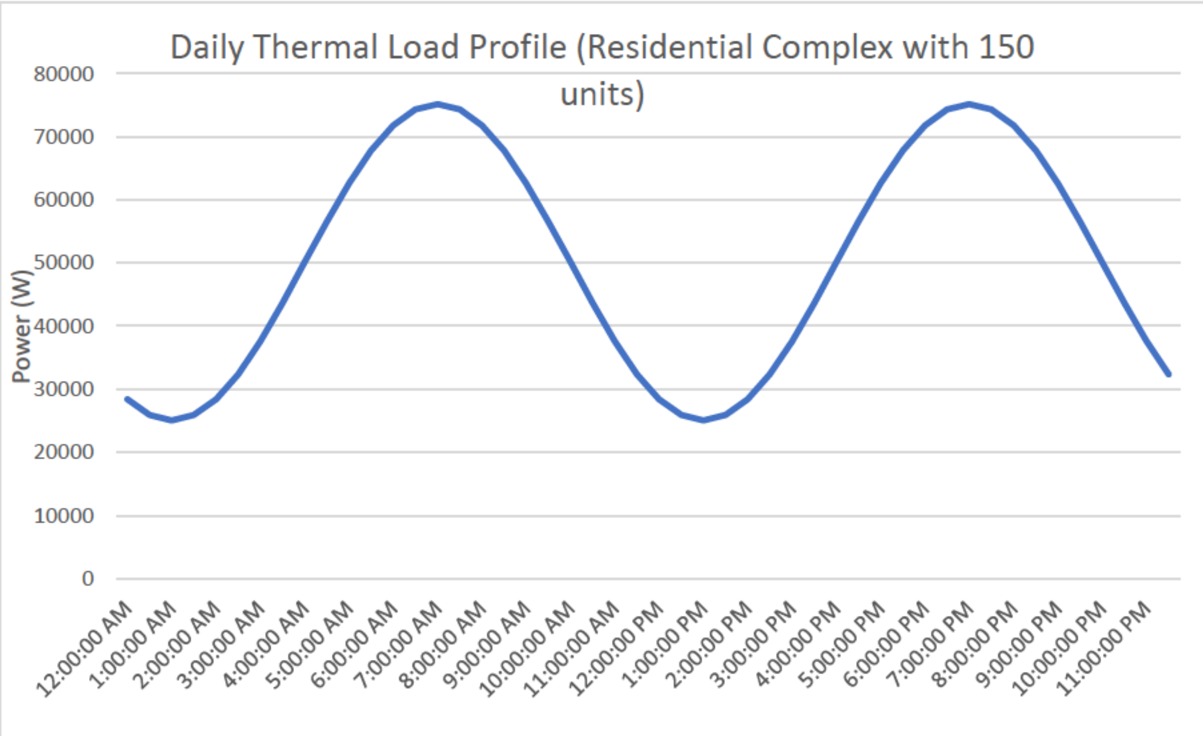

Figure 38: Daily Cyclic Demand Load Profile for a Residential Complex

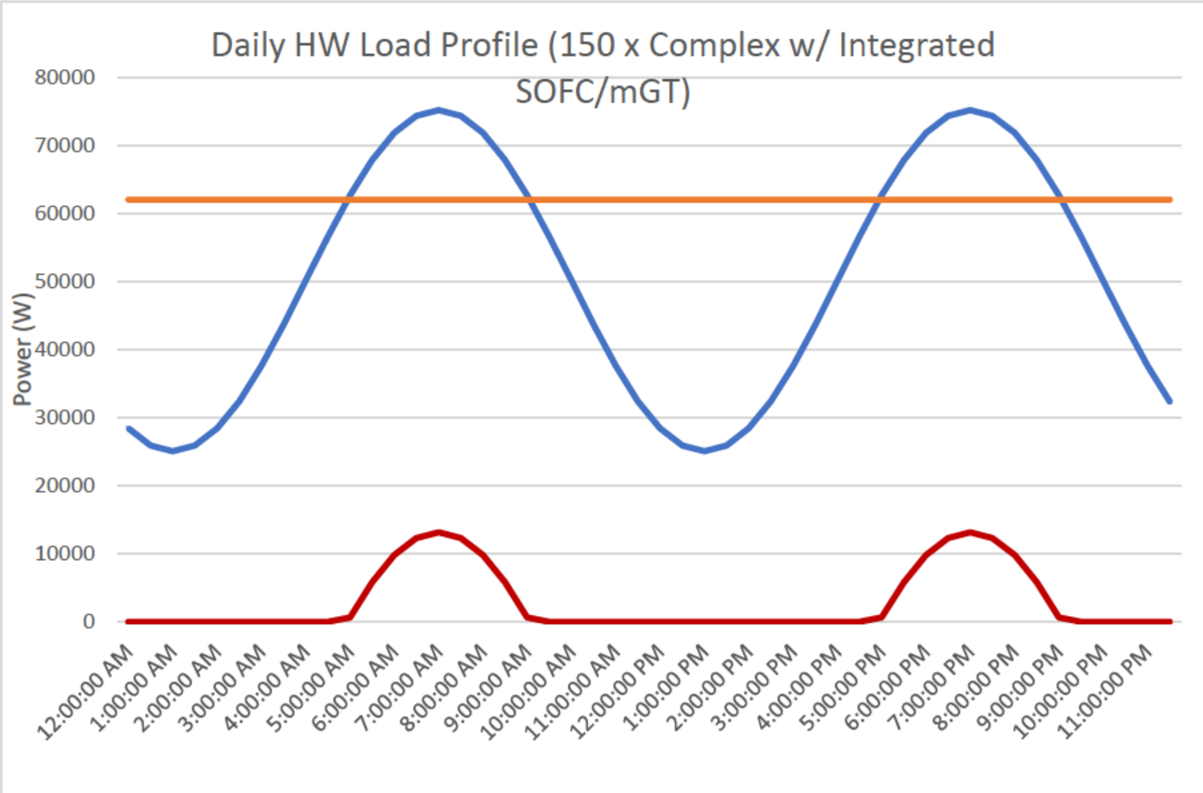

Figure 39: Resultant Thermal Demand with SOFC/mGT Integrated into a Residential Complex

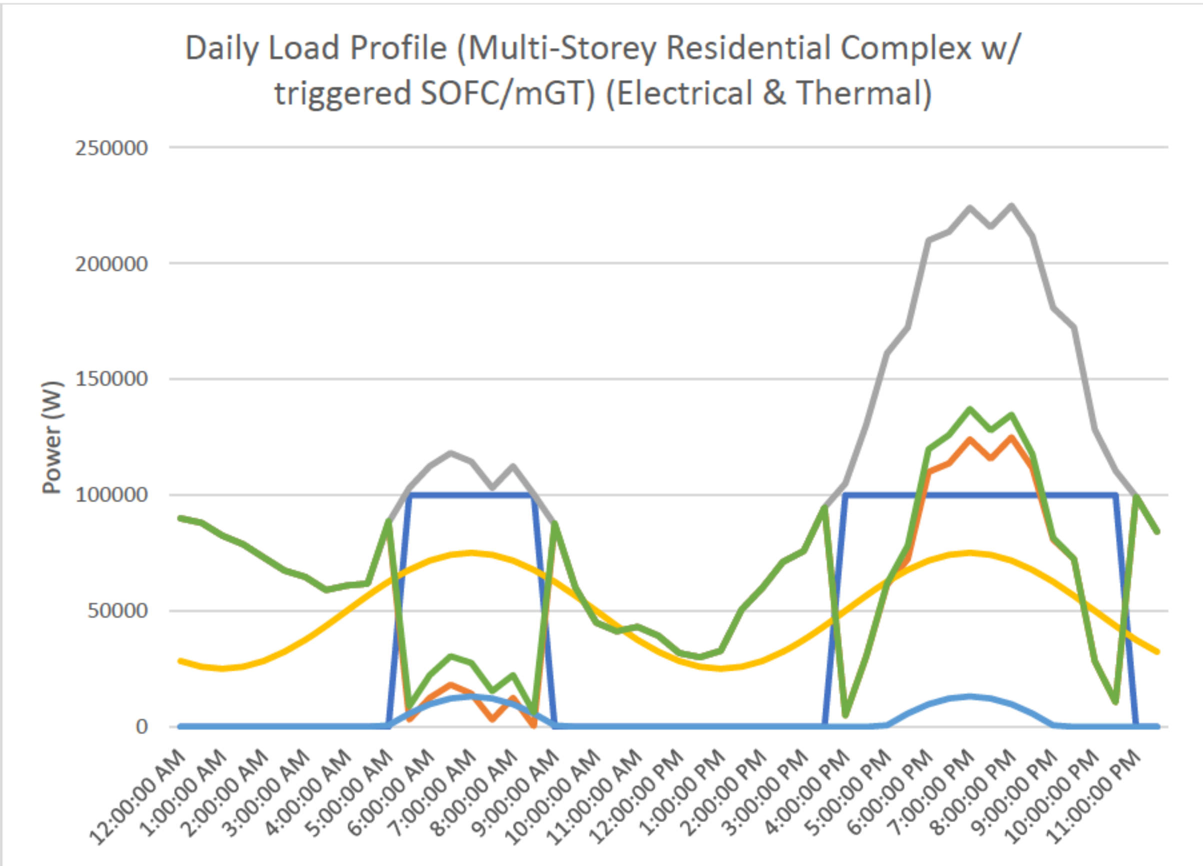

Figure 40: Daily Load Profile (Multi-Storey Residential Complex w/ triggered SOFC/mGT) (Electrical & Thermal)

3.4.2 Use Case 2

For use-case 2, integration of the SOFC/mGT system is modelled in the context of supplying a remote community hospital with export to local residential and commercial tenancies. Hospitals typically required a relatively steady electrical supply due to steady electrical base load during their 24-hour operation. Extra loading occurs at times during the day due to peak demand during meal prep and laundry, and running medical equipment such as autoclaves, all of which are load intensive. In this use-case, the hospital is required to supply a range of lighting and general power loads, as well as different heating equipment such as autoclaves and laundry equipment. In this use-case, the SOFC/mGT system would be located on-site, fed from gas tanks with sufficient capacity and pressure, with the system's low voltage output fed into the main switchboard with export capability.

In this methodology, electrical and thermal loads will be categorised and considered separately for modelling of the integrated SOFC/mGT supply. For the modelling of this use-case, the average daily load profile for representing the community hospital was approximated and charted in Figure 41 below, and the load of the community properties that the system is exporting to shown in Figure 42. Both of these loads that the SOFC/mGT is proposed to supply is seen in Figure 43. It was assumed that the premises are at 100% utilisation to model the worst-case load profile.

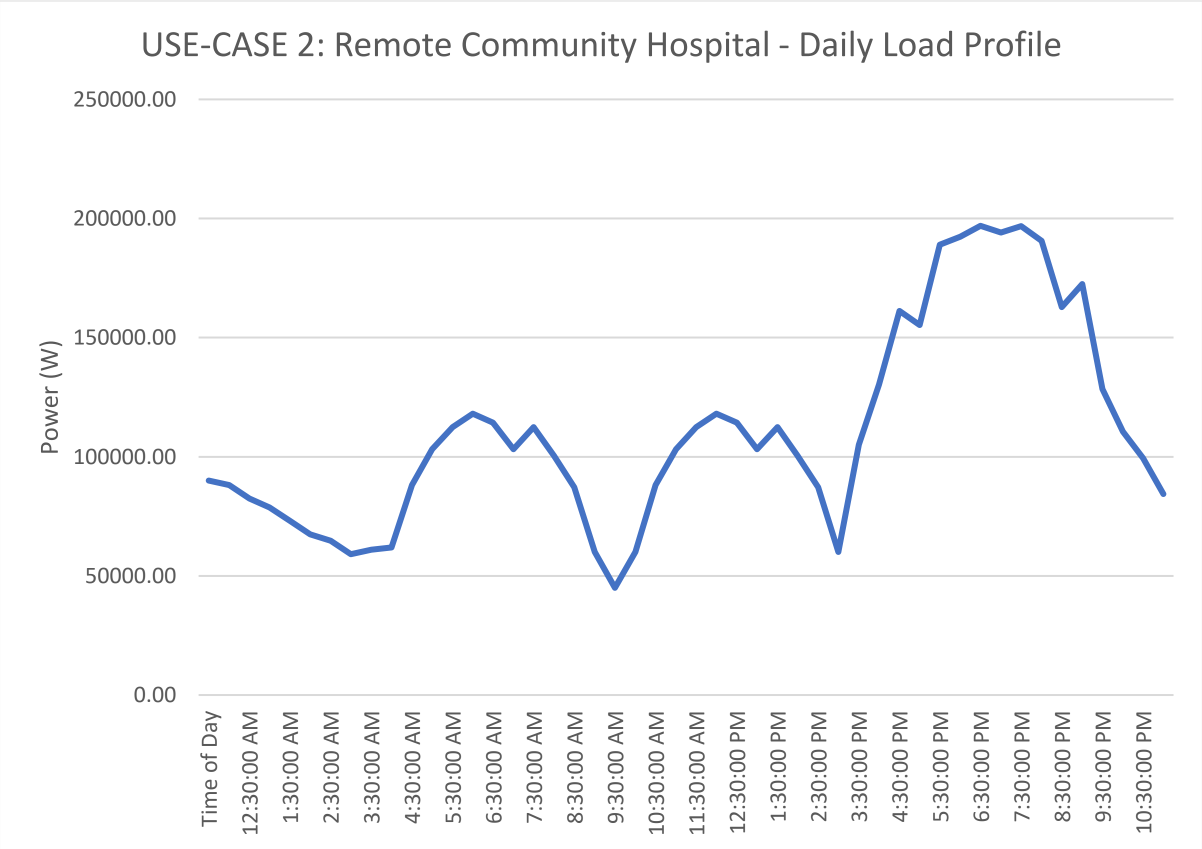

Figure 41: Daily Load Profile for Remote Community Hospital

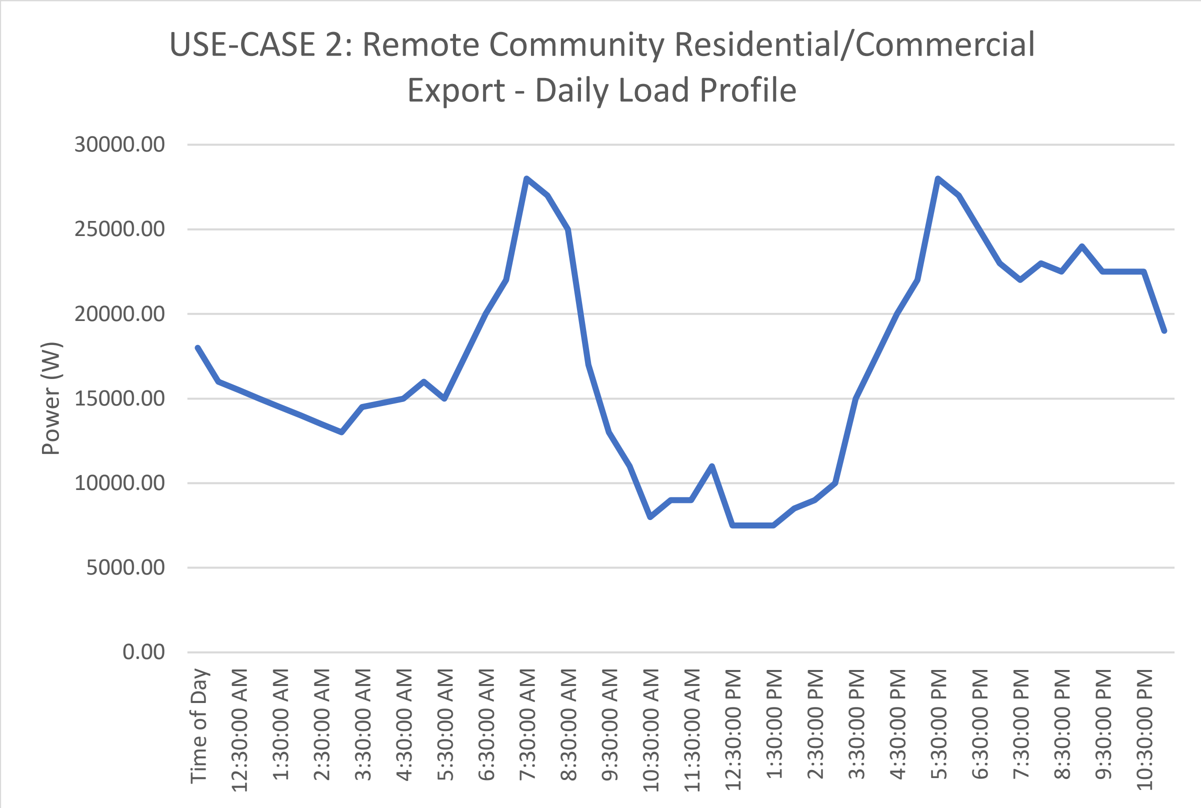

Figure 42: Daily Load Profile for Remote Community Residential/Commercial Loads

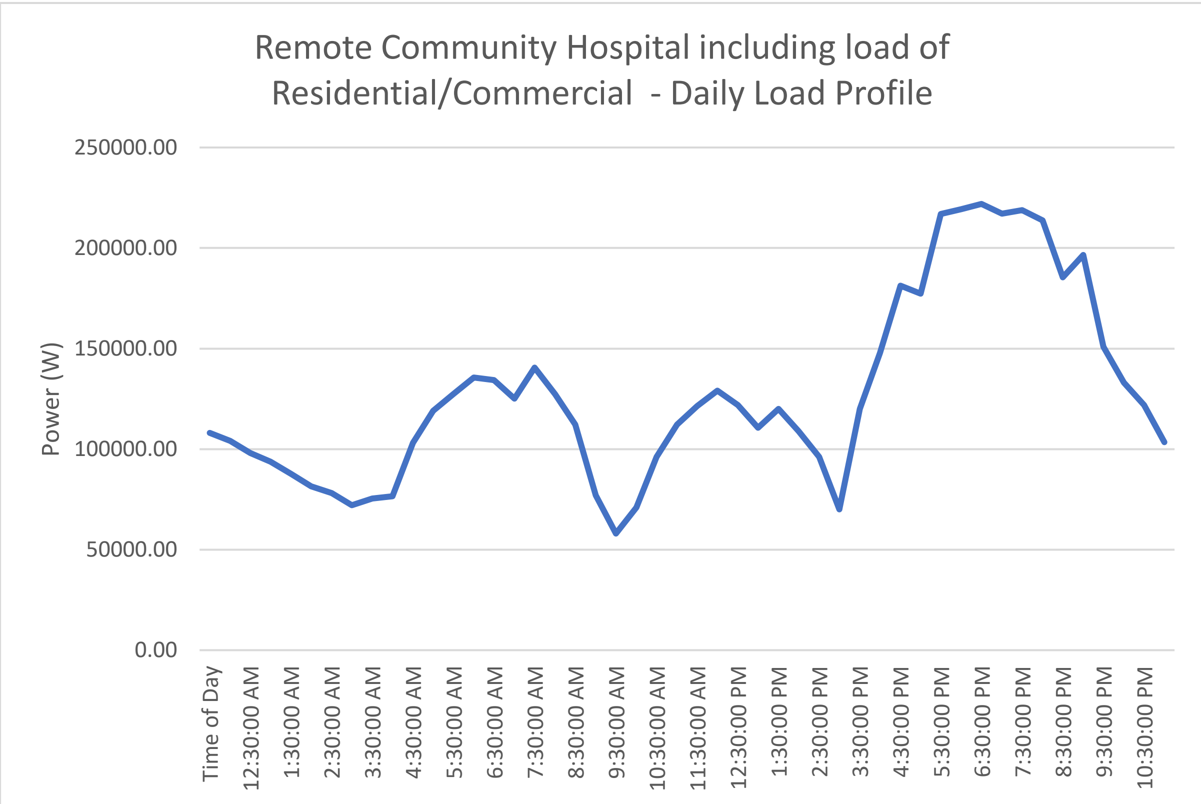

Figure 43: Daily Load Profile for Net Load of Remote Community Hospital with Connected Residential/Commercial Loads

Thermal Energy Load

The thermal load was estimated as a cyclic load due to the full-time operation of the proposed hospital, to supply equipment such as autoclaves, kitchen and laundry facilities. Figure 44 was formed to model approximate thermal demand required by the hospital equipment, the peaks of the load profile centred around the key peak times of the day. Both electrical and thermal loads were considered; for modelling purposes the thermal power equivalent (248.1kW-th) was directed to an insulated boiler, which then was able to provide hot water to the thermal loads modelled. For use-case 2, the thermal energy supply from the SOFC/mGT system was modelled with an assumed 50% loss in energy from output of the SOFC/mGT system to use by the hospital, resulting in 124kW-th from that specified for the system in Figure 43.

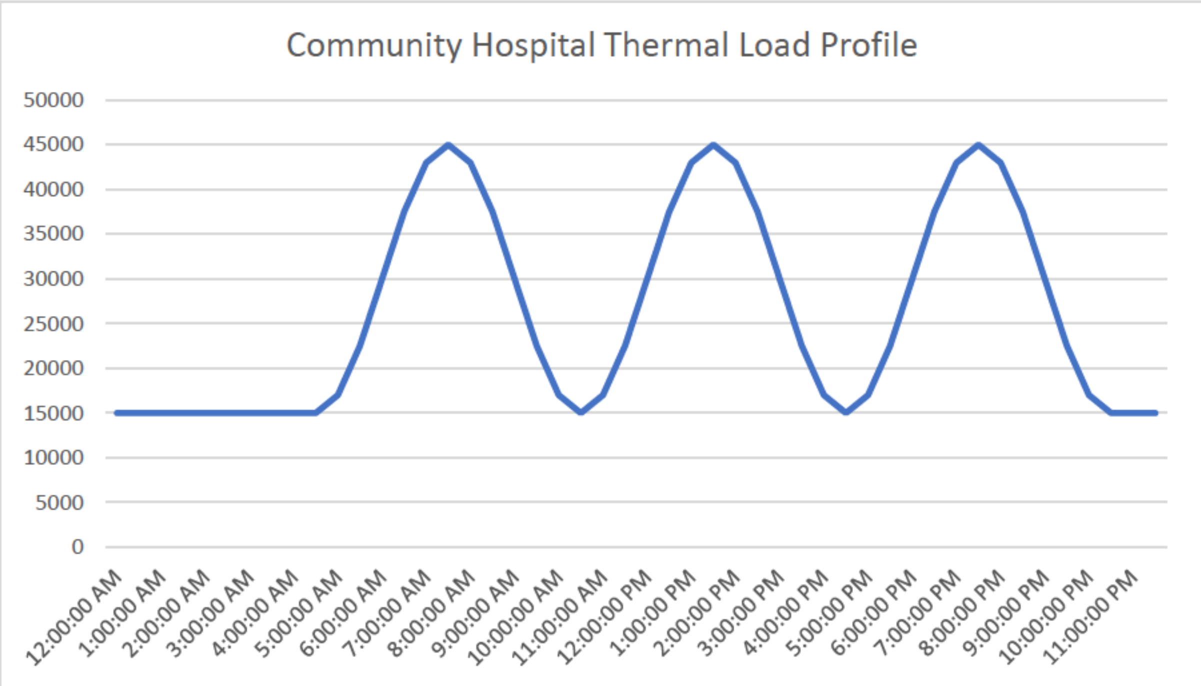

Figure 44: Approximated Daily Thermal Demand Profile for Remote Community Hospital

LOAD AND SUPPLY FACTORS SUMMARY **USE-CASE 2: SOFC/mGT 200kW Class**	
Parameter	Power Capacity
SOFC Fuel Heat Input	339.8 kW-th
MGT Fuel Heat Input	51.5 kW-th

SOFC Power Output	176.3 kW-AC
MGT Power Output	34.8 kW-AC
Auxiliary Power (System)	7.2 kW-AC
Net Power Efficiency (%, LHV)	52.1%
Total Energy Efficiency (%, LHV)	73% (85°C Hot Water)
SOFC/mGT Thermal Output	846.552 MBtu (IT)/hour = 248.1kW-th

Figure 45: SOFC/mGT system parameters defined

Integration

Integration of SOFC/mGT system in terms of supplying daily electricity demand of the hospital was formed, with an always-on approach (Figure 46) and supplying thermal demand with the always-on configuration was shown in Figure 47.

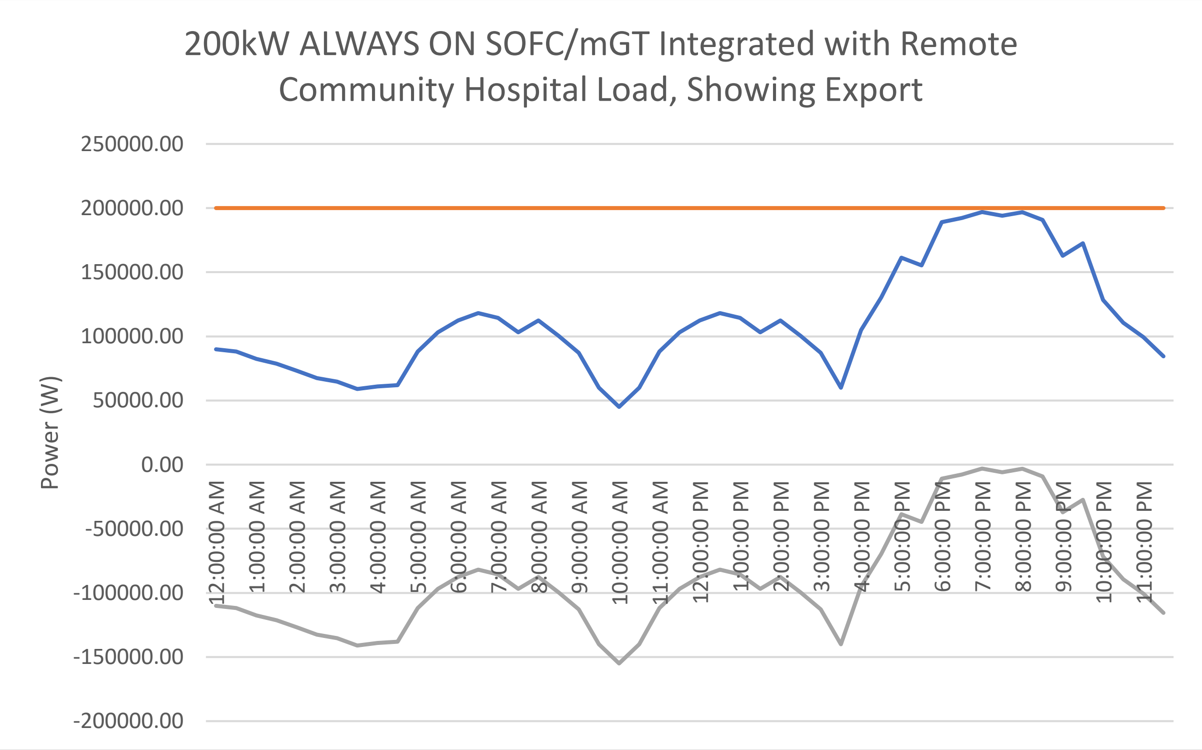

Figure 46: Approximated Daily Electrical Demand Profile for Remote Community Hospital showing Surplus Generated Electricity for Export

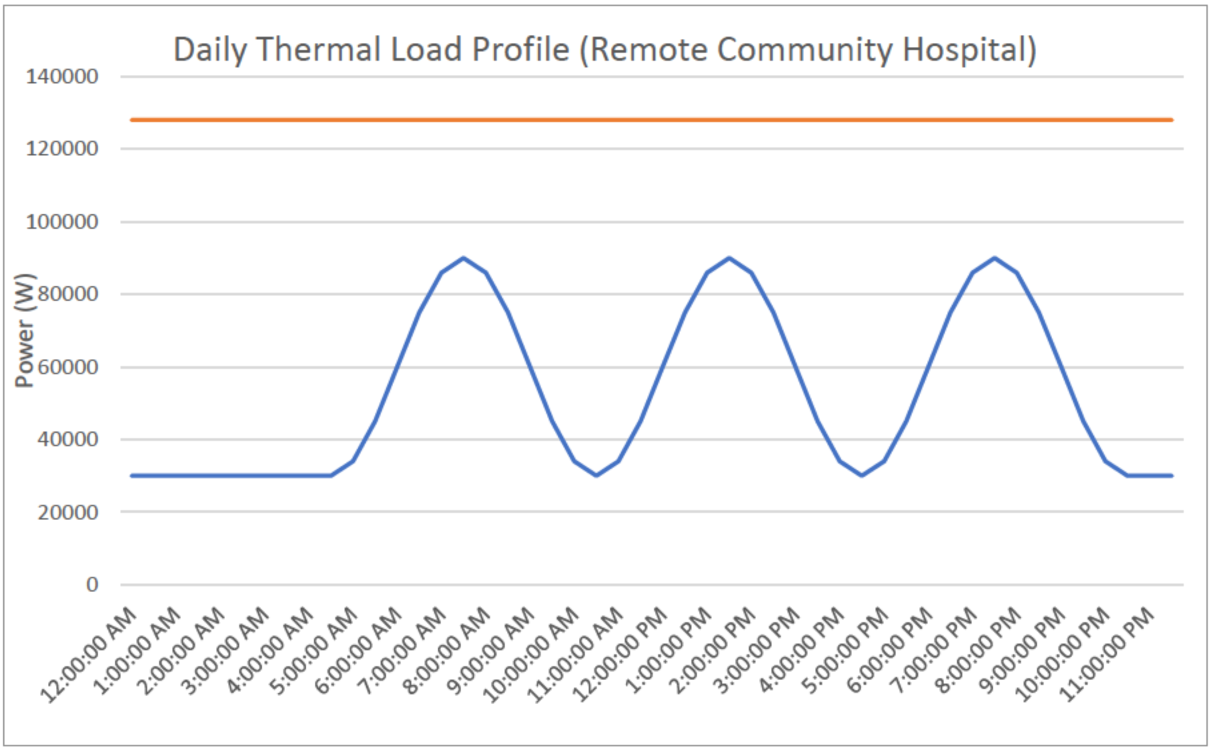

Figure 47: Approximated Daily Thermal Demand Profile for Remote Community Hospital

4.0 Results and Discussion

In order to understand the potential of hybridised solid oxide fuel cell and micro gas turbine hybrid technology in the context of providing a distributed and localised energy generation solution, this section will make sense of the calculations and figures developed within the report's methodology.

4.1 Key Advantages Overview

The methodology produced two key outcomes. The first part demonstrating the advantages of the SOFC/mGT system in context to other distributed power generation systems. It achieved this by evaluating advantages of the system, in order to assess and understand the value of the SOFC/mGT hybrid in cogeneration applications. By comparing this hybrid system to other relevant competing distributed supply sources, key advantages in terms of energy efficiency, start-up time, time-of-use and emissions are demonstrated.

Efficiency Advantages

Figure 10 shows a stark increase in net electrical efficiency with the addition of the SOFC equipment to the conventional micro gas turbine plant, as the TA200 standalone micro gas turbine system developed by Elliot Energy Systems (Figure 10, Left) has an electrical efficiency of 30% as opposed to the 55% net electrical efficiency of the Megamie Model 10 hybrid SOFC/mGT (Figure 10, Right). This demonstrates the key efficiency advantages allowed by the addition of the SOFC stacks when combined with conventional micro gas turbine plant, taken as increased electrical efficiency by approximately 25%.

As shown, the efficiencies for the SOFC/mGT hybrid has a typical efficiency range of 50 – 70%, which are superior to the efficiencies of all other fossil fuel generation plant types regardless of plant size. The efficiency for the Gas Turbine Combined Cycle plant is also high at a range of 50 – 60%, however this system is restricted to much larger generation capacities, starting at 10MW. This highlights that even with relatively low generation capacity of the SOFC/mGT hybrid, the energy efficiency is higher than competing generator systems.

Start-Up Time Advantages

Figure 13 shows the application of the fast start-up time of the SOFC/mGT system, with the SOFC/mGT Electrical Output curve triggered on when load of >50kW occurs, modelled to show full utilization of the hybrid system's full output capacity (200kW). Figure 15a and 15b shows the start-up times for various distributed generator types, specifically the large gas turbine systems having sub-40 minute start-up times which is competitive with SOFC/mGT hybrid. However, the 40 minute start-up time is still highlighted as a key advantage of this particular hybrid as it is fast and means the generation system can respond in near real-time as load variations occur on the connected load.

Time-Of-Use Advantages

Comparing against the example photovoltaic system shown in Figure 16, with a 40 minute startup time the SOFC/mGT system is able to supply loads at any time during the day, either through on-demand operation or timed operation, for use-cases that have consistent baseload and not necessarily predictable peak times throughout the day. Like the SOFC/mGT system, other fossil-fuel reliant distributed generation systems such as coal fired plant or larger gas turbine plant are not restricted to time-of-use, however some of the plant do suffer from longer start-up times as demonstrated in section 3.2.2.

Emissions - CO2

Figure 17 shows the CO_2, CH_4 and N_2O emissions factors across various fuel types, which shows the SOFC/mGT fuel type of natural gas/liquified natural gas (LNG) with the lowest emissions. To include the efficiencies of the generator plant combined with the fuel types to understand emissions from SOFC/mGT relative to other generators, Figure 19 collated values for plant and fuel type into a table. These values were then plotted in Figure 20, 21 and 22, to shows how both the plant efficiency and fuel type significantly affects resulting emissions. Figure 20 demonstrated that the SOFC/mGT hybrid has estimated 1614.9 kg of CO_2 when run at full output power of 200kW for 24 hours. Comparatively, GT Combined Cycle and SOFC stand-alone plant have very similar CO2 emissions to the SOFC/mGT system. Large GT plant have much higher CO2 emissions, at 2537.7kg run at the same conditions (200kW output, 24 hours), and coal-fired (black and brown coal) and stand-alone micro gas with significantly higher emissions, at 4443kg, 4616kg and 3948kg respectively.

Emissions - CH4

Figure 21 shows the CH4 emissions of plant running for 24 hours at 200kW output power in order to draw emission comparisons. Due to the low CH4 content in coal, the estimated CH4 emissions are much lower than all other generation types, at 1.481kg for black coal and 0.9874kg for brown coal. Relatively higher than this is the SOFC/mGT, SOFC stand-alone, and GT Combined Cycle, all sitting at CH4 emissions of 3.1418kg (GT Combined Cycle) to 3.2914kg. Higher again are emissions from large gas turbines at 4.9371kg and micro gas turbines at 7.68kg.

Emissions - N2O

Figure 22 shows the N_2O emissions of plant outputting 200kW for 24 hours. The SOFC/mGT system's N_2O emissions are lowest and equal to the GT Combined Cycle plant's emissions operating on natural gas, at a quantity of 1.4811kg. This compares to the N2O emissions of micro gas turbine at 2.304 kg, and higher again for coal fired at 9.874 kg for black coal, and 19.749 kg for brown coal.

Overall, the methodology demonstrates low emissions across the main exhaust emissions (CO_2, CH_4 and N_2O) considered in operation of the SOFC/mGT plant relative to other generation plant and fuel types. To summarise, the CO2 and N2O emissions for the SOFC/mGT system were the lowest amongst other relevant generators such as micro gas turbine, coal-fired (both black and brown coal), conventional gas turbine and combined cycle plant. For CH4 emissions, SOFC/mGT emissions were second only to coal-fired plant due to the low methane content of coal, however the SOFC/mGT is still amongst the lowest N2O emissions producer amongst the other generator types discussed.

4.2 Use-Case Application Overview

The second part of the Methodology demonstrated how the SOFC/mGT system may be utilised as a distributed cogeneration solution in the context of two use-cases. It achieved this by first considering site-specific load factors (Figures 31 – 32) with assumptions made regarding supply factors to evaluate the effectiveness of the SOFC/mGT system for cogeneration and energy export purposes. The proposed SOFC/mGT system was then detailed in terms of class and capacity (Figure 30) and scaled for optimal system sizing (Figure 33) to match projected load profiles. Finally, these load and supply factors were defined for proposed sites and were aggregated with the proposed integrated SOFC/mGT system to assess how effective the utilisation of the proposed system is within specific use-cases.

Use-Case 1

Use-case 1 explored three timing applications for the integration of the SOFC/mGT system. The shown in Figure 34, where the SOFC/mGT supplied the residential apartment complex with an 'always-on' timing mode, which took advantage of potential to export. This mode is advantageous if electricity export to the grid was economically beneficial, the analysis of which is outside the scope of this paper due to limited financial data available on SOFC/mGT systems. The technical benefits of this are that the electrical and thermal load is always guaranteed local supply from the system, however this method would come with losses due to the full operating output not being utilized (without financially beneficial grid export). The second method of integrating the system to supply property load is seen in Figure 35, with the level of system output trailing the load. This assumes that output of the SOFC/mGT can be scaled. This takes advantage of the SOFC/mGT output in a close-to real time supply (with delay shown as approximately start-up time) to trail demand, resulting in close to the full output capacity used at any time of use. The third method seen in Figure 36 with the SOFC/mGT operation triggered on at a nominal threshold of 100kW. This takes full advantage of the system's output while on which maximizes system efficiency. If grid export was not financially beneficial and the system were to only supply local loads, this timing configuration would result in maximized energy efficiency of the output of the SOFC/mGT system.

For use-case 1, the thermal energy demand of was modelled with an assumed 50% loss in energy from output of the SOFC/mGT system to use by the resident, resulting in 62kW-th from that specified in Figure 33. Thermal energy cannot be exported as electricity is, so within modelling the thermal supply/demand of the integrated system, all negative thermal demand values (which indicated export) were substituted with zero. A sinusoidal approximation was appropriate to model thermal demand due to cyclic nature of conventional hot water systems. Exhaust heat from SOFC/mGT system was modelled as always-on as long as the system was operating, as heat is created as a by-product and recuperated, dependent on electricity on-times. The values for thermal demand of a household were used to form Figure 37 for a typical household (8.016kWh daily), and then scaled up for the residential apartment complex (Figure 38) in use-case 1 with a projected daily thermal energy demand of 1202.4kWh-th. Figure 39 and Figure 40 demonstrates the resultant thermal demand, from an always-on thermal supply from the system. This demonstrates the use of recuperated heat from the SOFC/mGT system to satisfy total daily thermal demand (1202kWh), with minimal net power required to supplement the thermal demand at a value of approximately 70.2kWh-th, meaning a reduction of 1132.2kWh-th daily from recuperating the thermal energy in the exhaust, accounting for the approximate 50% loss from generation to end-user.

Use-Case 2

Use-case 2 explored the case of a SOFC/mGT system supplying a remote community hospital, with export to local residential and commercial premises. The daily load profile for the remote community hospital (Figure 41) and the remote community residential/commercial premises (Figure 42) combined into a net daily load profile (Figure 43). The SOFC/mGT system was scaled from the system specified in Figure 30 and defined in Figure 45, which was then used to supply the loads of the hospital and the connected remote community in Figure 43 with the SOFC/mGT always-on timing configuration. In this instance, the SOFC/mGT was sized to satisfy peak demand loads of the community hospital, with surplus energy exported to the community via the isolated distribution network.

The thermal demand was approximated as a cyclic sinusoid function to emulate the thermal demand of the hospital (Figure 44), based on projected peak times. The daily energy demand was projected as approximately one half of the electricity demand ie. 1260kWh-th and 2650.08kWh-e, daily. The thermal demand of the residential/commercial connected loads was not modelled due the designed nature of the SOFC/mGT system, which is unable to export thermal energy from its installation at the hospital. In distributed cogeneration systems such as in this SOFC/mGT application, the sizing of the system is dependent on the thermal energy that can be recuperated and supplied to the thermal demand local to the system, in this case demonstrated in Figure 46 to show a constant thermal supply

4.3 Limitations of Methodology

The main limitation of the methodology is the current developmental stage the SOFC/mGT hybrid systems are in. The SOFC/mGT systems installed are currently implemented only in a prototype/developmental stage and are currently running for testing and research purposes. However, as discovered throughout this project work, this testing and research data is unavailable outside of the companies and universities that operate and test them, and as such, only rudimentary technical data was available. As a result, this paper has been constrained to using limited data available to explore how SOFC/mGT systems may be utilized to achieve the aims of the dissertation. Furthermore, any data that would have allowed cost considerations, as were initial goals of this project, was not available. Therefore any cost analysis or comparisons to understand the system in terms of economic viability were not achievable at this stage, including conducting a sensitivity analysis of fuel types per generation method, as well as narrower evaluation of the system in terms of the economic sustainability metric were not achieved.

5.0 Conclusion

There were several key outcomes of this final year research project. The first and second aims of this project were to understand the fundamentals of SOFC and mGT technologies, as well as the design and operating principles of hybrid SOFC systems, by researching a broad range of literature and other reputable information sources that were cited and collated within the Background Information section. This aim was important to achieve as the research allowed the reader to understand fundamental concepts of the fuel cells, solid oxide fuel cell specifics, micro gas turbine technology, the physical, thermal and electrical coupling of these technologies to form the SOFC/mGT hybrid, the start-up process and the commercialisation aspects of this system.

Work towards the subsequent aims of this project was made within the Methodology section. Firstly, to validate the system in terms of sustainability metrics, Section 3.2 focused on the advantages of the SOFC/mGT hybrid, specifically fuel and plant efficiencies, start-up times, time-of-use, and emissions. Developing the methodology towards this aim was valuable to understand the key advantages that this specific hybrid enabled, offering relative insight via comparison against other relevant distributed generation systems. As a part of this, calculations and figures were developed in order to achieve the next aim of modelling the hybrid SOFC system as an energy efficient generation system, where the system was demonstrated as theoretically the most energy efficient fossil-fuel generation plant type.

In order to achieve the final aims of the paper as outlined in Section 1.2, the system was modelled as integrated into a localised network and assess the utility of the hybrid for localised generation purposes, in this case, through the application of the system to two use-cases within Section 3.4 of the Methodology. As outlined, these use-cases were firstly the residential apartment complex, and secondly, the case of the remote community hospital with export to local residential/commercial properties. This was done on a rudimentary basis due to limited technical data for the particular fuel cell hybrid chosen, and as such, basic projections of electrical and thermal load had to be made alongside several assumptions regarding load and supply conditions. The Recommendations for Further Work section gives insight to the reader as how further work could be made on modelling the integrated SOFC/mGT system as a distributed cogeneration system, as the author acknowledges this part of the methodology could be improved to better satisfy the original aims of the project but was only partially achievable due to the reasons outlined within the Limitations section.

Recommendations for Further Work

During this project work on the SOFC/mGT hybrid system and how it may be utilized in cogeneration applications, several avenues for further work were identified. Further research towards the development of this hybrid system is suggested in the following points:

- Understanding and modelling the application of the SOFC/mGT systems in industrial application that include primarily steam boiler systems;
- Understanding and modelling of the fuel cell hybrid combined with hydrogen systems, either in terms of generation and/or storage;
- Research into using reformed, high purity methane (or other hydrogen-rich gases) from renewable sources such as sewerage or biogas (landfill sites, etc);

- Calculating economies of scale that would allow SOFC/mGT hybrid systems to be financially viable as a distributed generation system;
- Research into additional technologies that may be installed with the SOFC/mGT plant that would improve operation factors;
- Research into additional, renewable fuel types that could be used to operate the micro gas plant;
- Research into improving the temperature and fuel flexibility of SOFC technology
- Research into different fuel cell technology to match microturbines and conventionally sized turbines;
- Control systems that allow different, optimal timing modes for the integrated system to local load, such as option of trailing operation (time of use) and/or triggered operation (on demand over a certain load) to take advantage of full rated output capacity;
- Sensitivity analysis that considers multiple compatible fuel types;
- Study into reliability advantages due to this fuel flexibility;
- Study into time-of-use compatibility with other generation systems for flexible and reliable distributed electricity supply.

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8.0 Appendices

8.1 Project Specification

ENG4111/4112 - Engineering Research Project

Project Specification

Student: Nikolas Zanetich (0061047847)

Title: Utilising Solid Oxide Fuel Cell Hybridised Technology as a Distributed Co-Generation Solution

Program: BENH, Electrical & Electronics

Supervisors: Dr. Les Bowtell, USQ

Sponsor: Ken Ash, Ener-G Management Group Pty Ltd

Enrolment: ENG4111 – ONL S1, 2020

ENG4112 – ONL S2, 2020

Project Aim: To investigate the utility and viability of solid oxide fuel cell (SOFC) technology, hybridized with gas turbine plant to alleviate increased network demand/ dependency due to medium term projected electric vehicle uptake.

Revision: Version 2, 9th April 2020 (Initially Submitted 18/03/2020; Supervisor Endorsed)

1. Research into current household/network demand, projected medium term household/network demand (accounting for EV uptake), reliance on grid and generation type, and other relevant background information.
2. Research into fundamentals of SOFC/GT combination systems, as a co-generation solution
3. Research/design/review into SOFC/GT systems and how they propose to be integrated into household/microgrid level
4. Modelling of SOFC/GT integrated systems on a household/microgrid/distribution level
5. Modelling of daily load profiles of SOFC/GT integrated power system, comparison against current household/grid demand profiles with analysis
6. Sensitivity analysis of LPG/electricity prices over the medium term, aiming to justify validity of SOFC/GT integrated system
7. Demonstrate validity via modelling and comparison between the SOFC/GT systems and other current grid and localized generation technologies
8. Evaluation against sustainability metrics (economics/societal/environment) throughout, where relevant
9. Conclusions, recommendations, and further work as discovered
10. Liaise with USQ supervisor (Dr. Bowtell, USQ) and industry sponsor (Ken Ash, Ener-G) over duration of research project.