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Master Thesis

SIMULATION OF LOAD PROFILES FOR THE APPLICATION OF A SOFC CHP SYSTEM AS CONTROLLABLE POWER PLANT OF THE FUTURE

submitted to

Chair of Energy Network Technology

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ABSTRACT

Electricity and thermal power are the two most important forms of energy in the contemporary world. Cogeneration (CHP) technologies combine the production of electricity and heat and can be divided into internal combustion engine based cogeneration systems, turbine based cogeneration systems and fuel cell based cogeneration systems. Solid oxide fuel cells (SOFC) are known to achieve higher electrical efficiencies and produce fewer emissions compared to conventional cogeneration technologies. Although, SOFCs are opening up new business fields, the commercial market segments for the SOFC technology are still very narrow. Therefore, the suitability of the technology for different applications needs to be tested to unlock new opportunities and market sectors. This report first gives a literature review in the form of a technical and economical comparison of SOFCs with commercial available gas turbines and gas engines in the power range up to 10 megawatts. The scope of this review covers a wide range of comparison parameters from efficiencies and emissions over power ramping behavior to maintenance efforts and comprehensive costs analysis. Furthermore, a model is compiled, which simulates the behavior of SOFC CHP systems to specify the suitability of the technology for different applications. The results of the simulation are combined with the technical and economical comparison, in order to determine the requirements for SOFC CHP systems as controllable power plants of the future. Compared to commercial reference technologies, SOFCs present major advantages regarding electrical efficiency, emissions and maintenance efforts. Nevertheless, additional development, especially on the fuel cell stack is necessary to improve performance degradation rates, initial costs and scalability. The results of the simulation show the suitability of SOFCs for multiple applications like continuous operation, prime with additional feed-in to the grid, island as well as supply of control energy. While SOFC CHP systems can compete with gas turbines and gas engines in most of the residual comparison parameters, especially the start-up time and ramp rates are very depended on the specific application. Nevertheless, every single application needs a very specific system configuration and operational mode in order to fulfill the technical and economical requirements. Furthermore, minor compromises regarding electrical and thermal cover ratio, surplus produced energy and full load hours are often indispensable. The major challenges occurred on the basis of the varying stack temperature, which is the limiting factor of the technology and strongly influences start-up time, ramp-rates and reliability of power production.

KURZFASSUNG

Strom und Wärme sind die beiden wichtigsten Energieformen in der heutigen Welt. Kraft-Wärme-Kopplungstechnologien (KWK) kombinieren die Erzeugung von Strom und Wärme und können grob in Verbrennungskraftmaschinen, Verbrennungsturbinen und Brennstoffzellen unterteilt werden. Im Vergleich zu konventionellen Kraft-Wärme-Kopplungstechnologien erzielen Festoxidbrennstoffzellen (SOFC) höhere elektrische Wirkungsgrade bei deutlich geringeren Emissionswerten. Obwohl Festoxidbrennstoffzellen in den letzten Jahren neue Geschäftsfelder erschließen konnten, ist die Anzahl kommerzieller Marktsegmente noch sehr gering. Aus diesem Grund ist es wichtig die Eignung der SOFC-Technologie für verschiedene Anwendungen zu testen, um in weiter Folge neue Geschäftsmöglichkeiten und Marktzugänge zu schaffen. Der erste Teil dieser Arbeit besteht aus einer Literaturrecherche in Form eines technischen und wirtschaftlichen Vergleichs von Festoxidbrennstoffzellen mit kommerziell erhältlichen Gasturbinen und Gasmotoren im Leistungsbereich bis 10 Megawatt. Dabei wird eine breite Palette von Vergleichsparametern wie Effizienz, Emissionen, Hochlaufgeschwindigkeiten, Kosten und Wartungsaufwand behandelt. Im darauf folgenden Teil der Arbeit wird ein Modell erstellt welches das Verhalten von Festoxidbrennstoffzellen simuliert um die Eignung der Technologie für unterschiedliche Anwendungen zu analysieren. Die Ergebnisse der Simulation und des technischen und wirtschaftlichen Vergleichs werden zusammengefasst um die Anforderungen an SOFC KWK Systeme als regelbare Kraftwerke der Zukunft zu ermitteln. Im Vergleich zu den konventionellen Technologien bieten Festoxidbrennstoffzellen große Vorteile im Bezug auf elektrische Effizienz, Emissionen und Wartungsaufwand. Zusätzliche Entwicklung ist insbesondere auf Basis des Brennstoffzellen-Stacks notwendig, um Degradationsraten, Investitionskosten und Skalierbarkeit des Systems zu verbessern. Die Ergebnisse der Simulation zeigen die Eignung der SOFC-Technologie für eine Vielzahl von Anwendungen wie das Bereitstellen von Grundlast, Spitzenlast und Regelenergie im Netzbetrieb sowie Inselanwendungen. Während Festoxidbrennstoffzellen in den meisten übrigen Vergleichsparametern mit Gasturbinen und Gasmotoren problemlos konkurrieren können, sind die Anlaufzeit und die Hochlaufraten sehr stark von der spezifischen Anwendung abhängig. Dennoch erfordert jede spezifische Anwendung eine spezielle Systemkonfiguration mit zugehörigem Betriebsmodus um die technischen und wirtschaftlichen Anforderungen zu erfüllen. Des Weiteren sind Kompromisse bezüglich des elektrischen und thermischen Deckungsgrades, der überschüssig erzeugten Energie und der Volllaststunden meist unverzichtbar. Der limitierende Faktor der SOFC ist hauptsächlich die stark variierende Stack-Temperatur, welche Einfluss auf die Anlaufzeit, die Hochlaufgeschwindigkeiten und die Zuverlässigkeit der Energieerzeugung hat.

PREFACE

The master thesis *Simulation of Load Profiles for the Application of a SOFC CHP System as controllable Power Plant of the Future* was compiled with the collaboration of the department of Stationary Solid Oxide Fuel Cells of the AVL List GmbH and of the Chair of Energy Network Technology. I would like to express my sincere thanks to Dr. Martin Hauth, Dipl.-Ing. Nikolaus Soukup as well as all the other colleagues from the department of Stationary Solid Oxide Fuel Cells and the AVL List GmbH for their great support. Furthermore, I would like to thank Univ.-Prof. Dipl.-Ing. Dr.techn. Thomas Kienberger and Dipl.-Ing. Lukas Kriechbaum for ensuring such good cooperation and assistance throughout the entire process. Finally, I would like to thank my family for their great support throughout my studies.

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ACRONYMS AND ABBREVIATIONS

BoP	Balance of plant
CAPEX	Capital expenditure
CHP	Combined heat and power
Cont.	Continuous
GE	Gas engine
GT	Gas turbine
HRSG	Heat recovery steam generator
IPP	Independent power producer
kW	Kilowatt
LE	Large engine
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
Masl	Meters above sea level
MW	Megawatt
SOFC	Solid oxide fuel cell
O&M	Operation and maintenance
OPEX	Operational expenditure
Oph	Operating hours
TCO	Total cost of ownership
W	Watt

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1 INTRODUCTION

Electricity and thermal power are the two most important forms of energy in the contemporary world. The average electrical efficiency of conventional power generation units is quite low and a large amount of the primary energy becomes waste heat. In the combined heat and power (CHP) technology, this waste heat can be captured and utilized for preparation of hot water or space heating. The currently most common CHP systems for commercial, institutional and residential applications are internal combustion engine based cogeneration system, turbine based cogeneration system and fuel cell based cogeneration systems. Solid oxide fuel cells (SOFC) achieve higher electrical efficiencies compared to conventional CHP technologies while only producing very little emissions. Although, SOFCs are opening up new business fields, the commercial market segments for the SOFC technology are still very narrow. Therefore, the suitability of the technology for different applications needs to be tested to unlock new opportunities and market sectors. [1-2]

The overall aim of this project is to compile a model, which represents the behavior of SOFCs to specify the suitability of the technology for different applications. Furthermore, the corresponding system configurations and operational modes should be determined. The results of the simulation are combined with a technical and economical comparison of SOFCs with conventional reference technologies, in order to determine the requirements for SOFC CHP systems as controllable power plants of the future.

Firstly, this report gives a literature review in the form of a technical and economical comparison of SOFCs with commercially available gas turbines and gas engines in the power range from 0,3 – 10,0 megawatts. The scope of this review covers a wide range of comparison parameters like efficiencies, emissions, power ramping behavior, maintenance efforts and comprehensive costs analysis, among others.

Secondary, the additional aim of this project is to simulate load following operations for SOFCs with MathWorks MATLAB to compile a model that can be utilized to verify the suitability of the technology for different applications. With the model the supply of control energy and the combined production of electricity and heat for industrial and residential applications are simulated for different SOFC system configurations and operational modes.

2 ASSIGNMENT

The overall aim of this work is to determine the requirements for SOFC CHP systems as controllable power plants of the future. Therefore, a technical and economical comparison of the SOFC system with commercial available gas turbines and gas engines is conducted. Furthermore, a simulation model is designed in order to specify the suitability of SOFCs for different applications as well as to determine the corresponding system configurations and operational modes. The results of the simulation are combined with the technical and economical comparison to determine strength, weaknesses and opportunities for the fuel cell technology.

2.1 Approach

The comparison between SOFC CHP systems, gas turbines and gas engines is primarily based on literature and internet research as well as various discussions with experts from AVL List GmbH. The relevant parameters of the comparison were compiled in cooperation with the AVL List GmbH and the Chair of Energy Network Technology.

The model for the simulation of load profiles will be compiled in MathWorks MATLAB with consideration of data from the literature research and system relevant input from the Stationary Solid Oxide Fuel Cell Department of the AVL List GmbH. The load profiles for the simulation are provided by the Chair of Energy Network Technology.

3 THEORETICAL BACKGROUND / STATE OF THE ART

In this chapter the SOFC is compared to conventional reference technologies in order to determine the suitability of the systems as controllable power plant of the future.

3.1 Solid oxide fuel cells

A solid oxide fuel cell is a very efficient way to convert chemical energy of a fuel and an oxidant directly to electrical power without intermediate steps. Beside the by-products heat and water, the SOFC only produces very little emissions. [1-2]

SOFC CHP systems consist out of three elementary sub-systems: the fuel cell stack, the fuel processing unit and the power conditioning system. The purpose of the fuel processor is to convert the fuel into a hydrogen-rich inlet stream to the fuel cell stack via steam reforming. The fuel cell stack utilizes the chemical energy of the fuel and converts it into electrical and thermal energy. The power conditioning system converts the DC voltage that is generated by the stack, into the specific form of electrical power that is requested by the end user. [1-2]

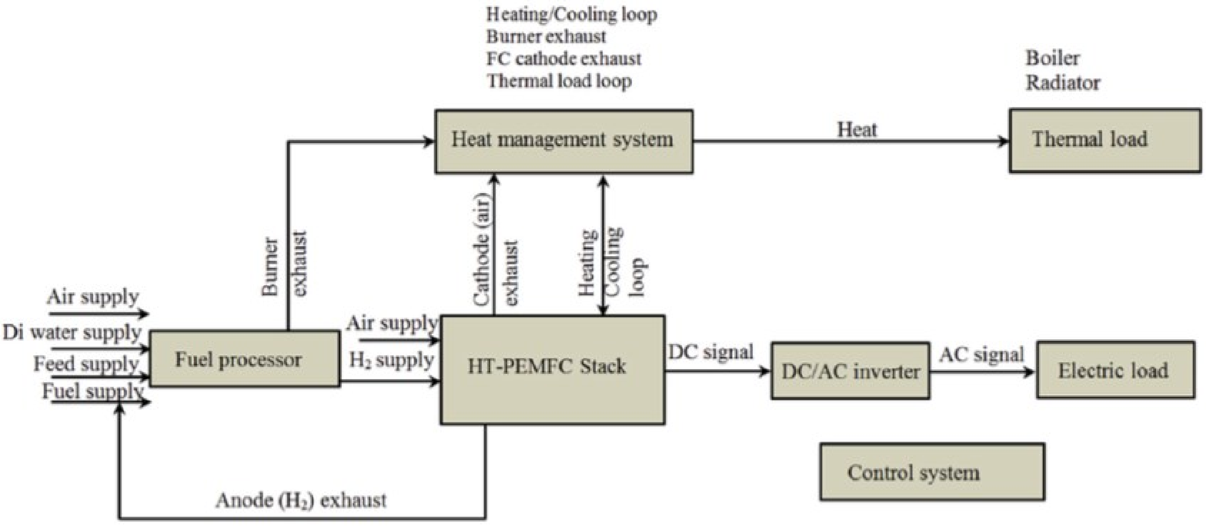


Figure 3-1: SOFC system layout [1]

SOFC systems typically operate in the temperature range of 700 - 1000 °C. Heat is mainly recovered in form of hot water but also steam with pressures up to 10 bars can be produced. Different to other fuel cell technologies the SOFC utilizes metal oxide ceramic materials in the membrane electrode assembly. As a result of high operating temperatures, nickel can be used as a catalyst instead of more expensive precious metal catalysts. [1-2]

The typical main components of a SOFC CHP system are given in the list below. [1,3]

- SOFC stack
- Inverter
- Afterburner
- Base frame
- Air intake system (Blowers)
- Air heat exchanger
- Exhaust heat exchanger
- Anode gas heat exchanger
- Exhaust gas cleaning system
- Gas supply
- Fuel processing unit
- Monitoring & control system
- Start-up system
- Air filter

3.2 Analysis of reference technologies

Currently, SOFCs are at the pre-commercial stage for stationary power generation. The SOFC technology must compete with established conventional CHP technologies in order to be commercially successful. These conventional engines burn fuel to heat a specific volume of gas, followed by expansion of the hot gas in a turbine or piston machine driving a generator. Although these conventional technologies have lower electrical efficiencies and higher emissions compared to high temperature fuel cells, they tend to be surprisingly economic because of long-term development, optimization and mass production. [1-2]

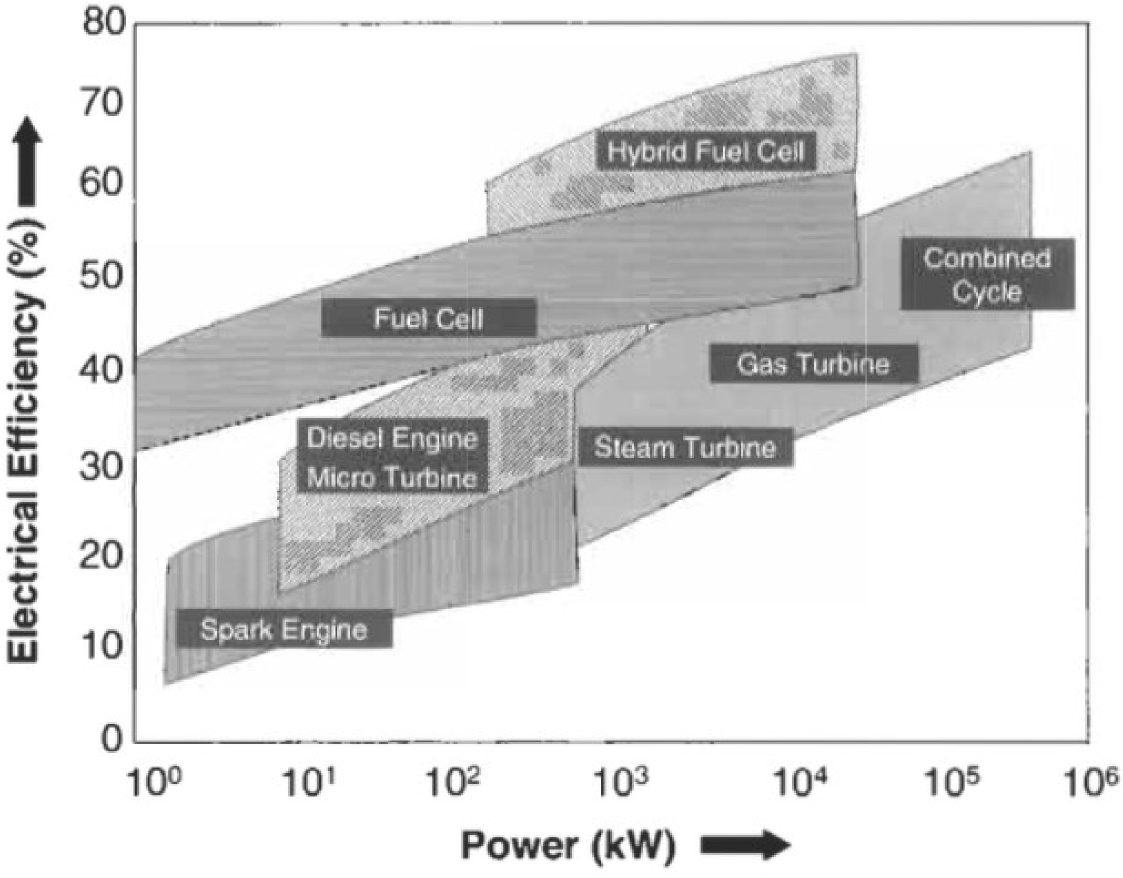


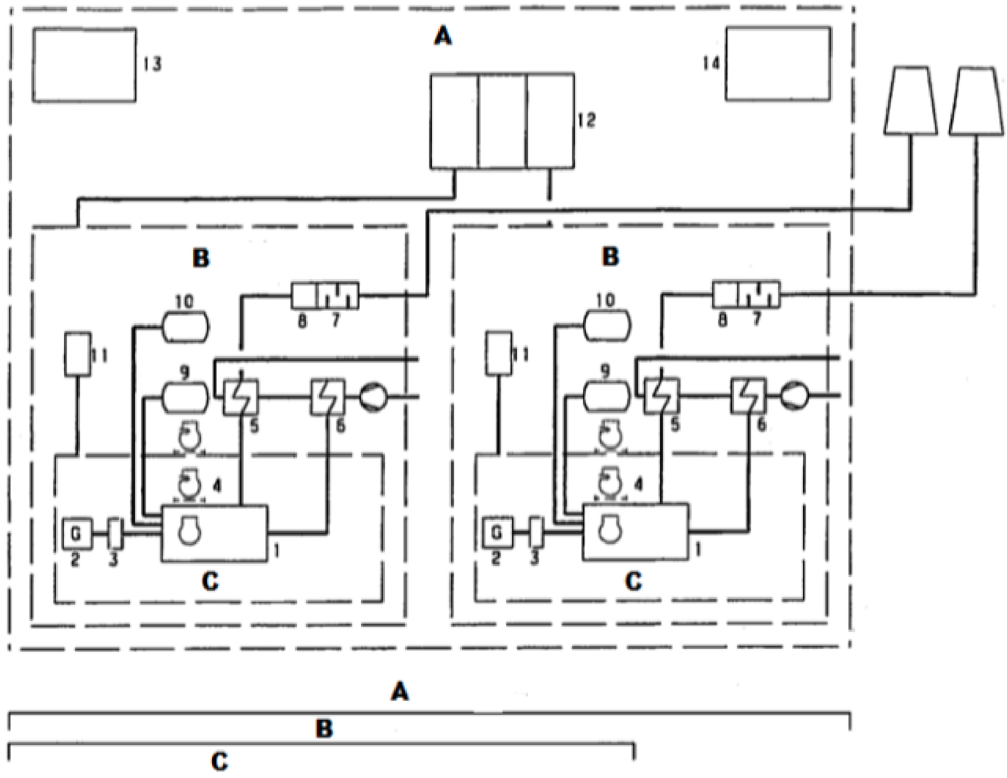
Figure 3-2: Electrical efficiencies and power ranges [2]

3.2.1 Gas engines

Gas engines are a mature and widespread technology that is used for many kinds of power generation, from small and mobile units to large industrial engines of multiple megawatts. Gas engine power generation units are also suitable for CHP applications in commercial and industrial applications of less than 5 MW. Natural gas is the preferred fuel for spark ignition engines although a large variety of fuels can be utilized. While smaller gas engines produces hot water, larger systems can also be designed to produce low-pressure steam. [4]

The typical main components of the gas engine-powered genset (combination of an engine and an electrical generator) and the corresponding CHP package as per DIN 6280-14 are given in the list below. [5]

- Combustion engine (1)
- Generator (2)
- Coupling (3)
- Air filter (4)
- Exhaust heat exchanger (5)
- Cooling water heat exchanger (6)
- Exhaust silencers (7)
- Exhaust gas cleaning system (8)
- Gas supply (9)
- Oil supply (10)
- Monitoring & control system (11, 12)
- Air intake system (Turbocharger) (13)
- Start-up system (14)
- Base frame



A	Combined heat and power plant (CHP)
B	CHP set
C	CHP genset

Figure 3-3: Conventional CHP system layout

3.2.2 Gas turbines

Like gas engines, gas turbines are an established technology for distributed generation applications in a power range from only a few hundred kilowatts up to about several hundred megawatts. Gas turbines usually produce high-quality heat that is recovered in form of steam, which is considered an important advantage of the technology. [4]

The typical main components of the gas turbine genset incl. CHP based on DIN 6280-14 are given in the list below. The numbers next to the single components refer to *Figure 3-3*. [6][7]

- Combustion turbine (1)
- Generator (2)
- Gearbox (3)
- Air filter (4)
- Exhaust heat exchanger (5)
- Cooling water heat exchanger (6)
- Exhaust silencer (7)
- Exhaust gas cleaning system (8)
- Gas supply (9)
- Compressor cleaning skid (10)
- Monitoring & control system (12,13)
- Air intake system (Compressor) (13)
- Start-up system (14)
- Base frame

3.3 Performance comparison

The aim of the technical and economic performance comparison is to determine the advantages and disadvantages of SOFCs to conventional power generating systems.

3.3.1 General information / Properties

SOFC systems are compared to industrial gas turbines and gas engines for the power generation application incl. CHP in the power range from 0,3 – 10,0 MW. The primarily considered fuel for this performance comparison is natural gas. These conditions apply to every compared parameter unless otherwise stated. The mainly considered manufactures in this comparison are listed in *Table 3-1*.

Table 3-1: Manufacturers

SOFC	Gas turbine	Gas engine
Bloom Energy, Fuel Cell Energy, SOLIDpower and Convion	Kawasaki Gas Turbines Europe GmbH, Dresser-Rand and Siemens AG	General Electric, Caterpillar and Wärtsilä

The results of the comparison represent the requirements for the application of the SOFC as controllable power plant of the future as well as the suitability of the SOFC for substitution of conventional technologies in specific applications.

3.3.2 Fuels

The primarily fuel considered in this performance comparison is natural gas. Nevertheless, it is shown that a broad range of fuels can be utilized in all three systems. Specific fuels like for example landfill gas or sewage gas often require a more complex exhaust gas treatment and fuel gas cleaning as well as specific maintenance which usually results in a raise of costs. An advantage of the SOFC system could be a multiple fuel operational mode, because there is no need to shut down the system while changing from one fuel type to another, this is not possible for large engine systems. [5]

Table 3-2: Fuels

SOFC	Gas turbine	Gas engine
Natural gas, biogas, diesel, LNG, LPG, dual fuel, wood-gas, methanol, ammonia, landfill gas, hydrogen, ethanol, propane, butane, biodiesel	Natural gas, methane, LNG, propane, butane, LPG, naphtha, diesel, jet fuel, fuel oils, heavy oil, ethanol, bio diesel, methanol, biogas, landfill gas, syngas	Natural gas, biogas, landfill gas, sewage gas, steal gas, flare gas, propane, wood gas, pyrolysis gas, coke gas, coal mine gas
[2][8]	[9-10]	[5][10-11]

3.3.3 Electrical efficiency

The electrical efficiency of gas turbines and gas engines varies widely over the range of their nominal power output. In contrast the electrical efficiency of SOFC systems is constant over the considered power range because of the modular and extensible stack-built design. Therefore, electrical efficiency values of 60 % are no longer just a future target value for SOFC systems and have already been demonstrated for smaller systems. [1]

Table 3-3: Electrical efficiency

Power range	SOFC	Gas turbine	Gas engine
0,3 – 1 MW	55 – 60 %	-	34,5 – 42,8 %
1 – 2 MW	55 – 60 %	26,0 – 26,9 %	36,4 – 43,3 %
2 – 5 MW	55 – 60 %	29,7 – 32,9 %	40,4 – 45,7 %
5 – 10 MW	55 – 60 %	30,6 – 33,6 %	46,0 – 50,0 %
	[1][12-15]	[16-18]	[11][19-26]

3.3.4 Degradation

With proper maintenance gas turbines as well as gas engines show basically no decrease in performance while SOFCs present much higher efficiency losses. The SOFC stack is normally not maintained, but rather changed after about 40.000 oph. The stack exchange intervals can also be shorter depending on the SOFC stack materials and operating temperatures. [27]

Table 3-4: Degradation

Degradation	SOFC	Gas turbine	Gas engine
Efficiency decrease	0,3 % every 1000 oph without maintenance	< 1,0 % after 24.000 oph incl. maintenance < 7,0 % after 3 – 5 years without maintenance	1,0 % after 24.000 oph incl. maintenance
	[28]	[29-30]	[31]

3.3.5 Electrical part load efficiency

The electrical efficiency decreases for gas turbines and gas engines while operating at partial load. The electrical efficiency of SOFC stacks experiences an increase during part load operation because of relatively decreasing voltage losses at lower current densities. The increase of efficiency could be influenced negatively in full SOFC CHP systems because of parasitic losses in the auxiliary systems. [1]

Table 3-5: Electrical part load efficiency

Load point	SOFC	Gas turbine	Gas engine
50 %	> 60,0 %	28,7 %	~ 42,0 %
100 %	55,0 – 60,0 %	37,0 %	~ 46,0 %
Difference (50/100%)	+/- 0,0 %%	- 15,0 to - 25,0 %%	- 8,0 to - 10,0 %%
	[1][4]	[32-33]	[32-34]

Large power plants, which consist out of multiple engines, have a different approach of performing part load operation. Single engines can be disconnected from the grid while the majority of the remaining engines continue operating at full load. As a result, gas engine power plants can achieve minimal efficiency drops of < 1 % at 50% load. [32]

3.3.6 Total efficiency

While the total efficiency (combined heat and power) strongly depends on the specific usage of heat, all three systems can achieve values above 90 %.

Table 3-6: Total efficiency

SOFC	Gas turbine	Gas engine
up to 95 %	up to 95 %	up to 95 %
[15][35]	[36]	[36]

3.3.7 Exhaust gas temperature for heat recovery

The exhaust gas temperature of gas turbines and gas engines are both higher than for SOFC systems. A different result can be observed if the minimal exhaust gas cooling temperature is considered. In order to avoid damage to the heat exchanger by acidic condensate, the minimal exhaust gas cooling temperature for gas engines is limited to approximately 120 °C. SOFC CHP systems include a built-in desulphurizer in the fuel processing unit which could provide a far more efficient usage of heat. [1][5]

Table 3-7: Exhaust gas temperature without heat recovery

SOFC	Gas turbine	Gas engine
≥ 200 °C	465 – 583 °C	325 – 425 °C
[1][15]	[18][37-39]	[37-38]

3.3.8 Scalability

Single unit gas turbines, except for micro turbines, tend to have a higher maximum power output than gas engines or SOFCs. In order to build up a power plant, multiple single units are combined which results in a higher maximum power output. The modular design of SOFC systems has no maximum power limitations except regarding the available footprint.

Table 3-8: Scalability

Units	SOFC stack	Gas turbine	Gas engine
Single unit	0,05 – 12,5 kW	1,7 – 450 MW	0,1 – 18 MW
Multiple units	no limit	no limit	no limit
	[40-41][44]	[16-18]	[42-43]

3.3.9 Footprint

In order to compare the system size of the three systems, the footprint of mobile container solutions seems to be more reliable than comparing full sized power plants. Gas turbines only need very little space per MW, which is a huge advantage of this technology. The footprint of SOFCs is much larger compared to gas turbines or gas engines because of the comparatively low power density of the stack. It can be expected that the footprint of SOFC systems will be smaller in the future because of stack improvements.

Table 3-9: Footprint - Container solutions

Container solutions	SOFC	Gas turbine	Gas engine
MW per 40 ft. container	0,5	4,5	1 – 1,4
	[44]	[45]	[46-47]

3.3.10 Start-up time

A definite advantage of gas engines and gas turbines compared to SOFC sytems is the faster start-up time to full power. The start-up time of SOFC systems primarily depends on the time of starting the reforming process and pre-heating the stack. [1-2]

Different to modern combined cycle power plants, the start-up time of gas turbines is mostly independent to the standstill time. During start-up gas turbines raise the spin of the compressor, ignite, ramps-up turbine acceleration to self-sustaining speed, synchronizes to the grid and adapt to the requested load in approximately 15 minutes. For combined cycle operation, the heat recovery steam generator (HRSG) causes additional thermal problems. Gas engines utilize high efficiency lean-burn technology that can reach full load in two to seven minutes under hot start-up conditions. In order to meet hot start-up conditions, the temperature of the cooling water is maintained above 70 °C, the bearing are continuously lubricated and the engine already is slowly cycling. The start-up time is also not influenced by the amount of time the engine had been shut down. Cold start-up is not usual for the gas engine. [48-49]

Table 3-10: Start-up time

Start-up time	SOFC	Gas turbine	Gas engine
Cold start-up	4 – 6 h	15 min	2 – 6 h
Hot start-up	< 60 min		2 – 10 min
	[1-2][44]	[48]	[48-49][50]

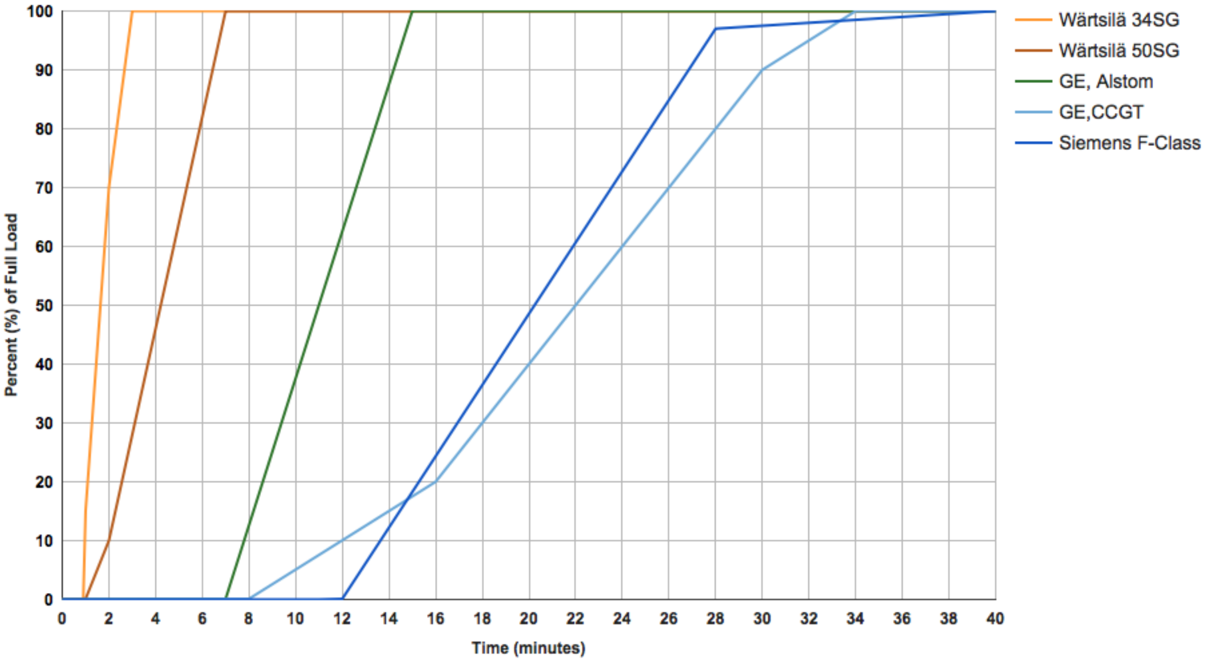


Figure 3-4: Start-up times [60]

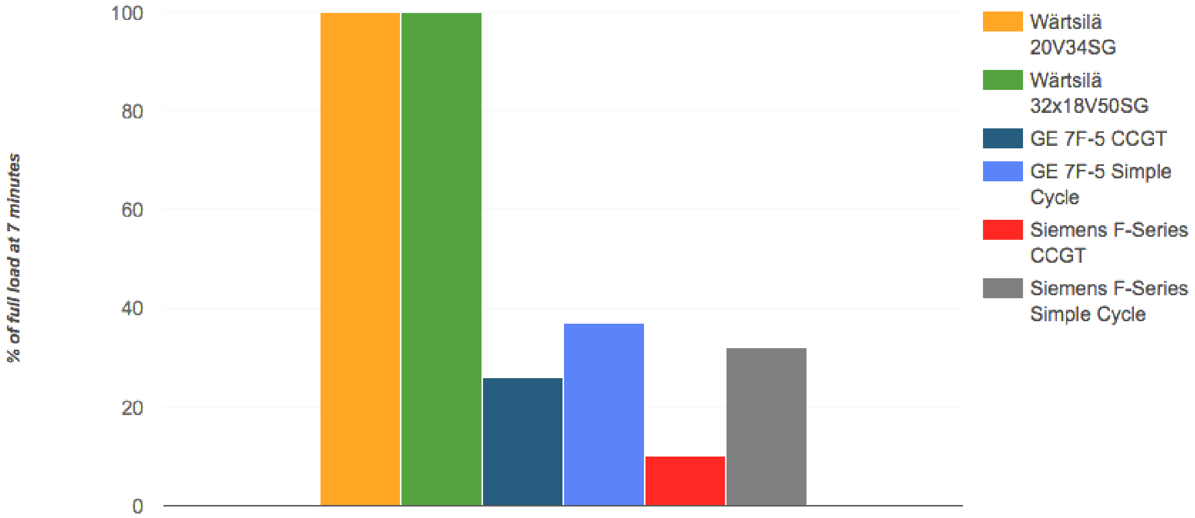


Figure 3-5: Starting load delivery [53]

3.3.11 Ramp-rates

The power ramp-up rate of SOFC systems primarily depends upon the temperature of the stack. Higher temperatures of the stack lead to higher ramp-up rates while the ramp-down rate is not influenced by temperature. The temperature behavior of SOFCs works in a way that a ramp-up of power basically leads to an increase in temperature, while ramping-down power results in a decrease of temperature. Large conventional power plants, which are built out of multiple units, mostly present much higher ramp rates depending on the number of units and system configurations. [44][51]

Table 3-11: Ramp-rates of single unit power distribution systems

[% of nominal electrical power output per min]	SOFC	Gas turbine	Gas engine
Ramp-up rate	3 (at lowest temperature where current can be drawn) 100 (at operating temperature)	20 – 25 (> 100 MW) 88 (35 MW)	48 – 50
Ramp-down	200	20 – 25 (> 100 MW) 88 (35 MW)	50 – 60
	[44][52]	[45][51][53-54]	[51][55-57]

3.3.12 Power modulation

Power modulation for one single SOFC unit is only limited by the heat loss of the system. In case of modular design, single units can be shut down completely in order to achieve a wider power modulation range. Considering economic aspects all systems should be operating at full load to achieve reasonable amortization periods. [44]

Table 3-12: Power modulation

	SOFC	Gas turbine	Gas engine
% of nominal electrical power	(0 –) 50 – 100 % > 50 % thermally self sustaining < 50 % additional heating, efficiency losses	40 – 100 % 60 – 100 %	10 – 100 % 35 – 100 %
	[44]	[54][58-59]	[50][60-61]

3.3.13 Grid synchronization time

SOFC CHP systems utilize an inverter to supply the electrical energy to the grid. The different characteristics of fuel cell systems compared to conventional inverter based power production plants lead to additional requirements in order to comply with technical and legal boundary conditions. Different to inverter based photovoltaic systems SOFC CHP systems produce electricity and heat and can be operated either electricity or heat controlled. Additional to the inverter, SOFCs needs a step-up converter. The step-up converter transforms the fluctuating DC output voltage from the stack to a constant intermediate circuit voltage, which than can be inverted to the required AC voltage for feed-in to the grid. Normally the grid failure detection reaction time is too long to support an interruption-free island operation without any kind of puffer storage. [62]

Different to SOFC systems, gas turbines and gas engines are connected to the grid by a generator. While cycling at rated speed, it takes the generator about half a minute to connect to the grid. Under hot start-up conditions gas engines need approximately 2 minutes for the full start-up and synchronization process. This typically includes pre-lubrication, ignition, accelerating to rated speed and synchronization to the grid. Gas turbines need approximately 15 minutes for the full start-up and synchronization process under hot start-up conditions. This typically includes increasing the compressor spin to reach firing speed, ignition, acceleration to self-sustaining speed and synchronization to the grid. [49-49][63]

Table 3-13: Grid synchronization time

Grid synchronization time [min]	**SOFC (Inverter)**	**Gas turbine (Generator)**	**Gas engine (Generator)**
Hot start-up	2	0,5 – 15	0,5 – 2
	[63]	[48][63]	[48][63]

3.3.14 Efficiency of inverter / generator

The efficiency of the generator and the inverter between 50 – 100 % load is mostly even. Nevertheless, the additional needed step-up converter for SOFC systems can reduce the overall efficiency of the full electricity transformation path down to 90 % and lower. [44][62][65]

Table 3-14: Efficiency of inverter / generator

SOFC (Inverter + Step-up converter)	**Gas turbine / Gas engine (Generator)**
Inverter: 95 – 98 % Step-up converter: 97%	95 – 98 %
[44][65]	[5]

3.3.15 Influence of altitude on performance

Performance decreases of SOFC systems at higher altitudes are mostly a result of losses in blower efficiency as well as minor impacts of the lower O_2 partial pressure in the stack. [44]

The power output of gas turbines decreases proportionally with altitude. Although supercharging can be used, a large amount of additional energy is necessary which negatively influences the economic efficiency of the system. Differently gas engines can maintain maximum output up to approximately 2000 masl as a result of radiator cooling and turbocharging. [60][66]

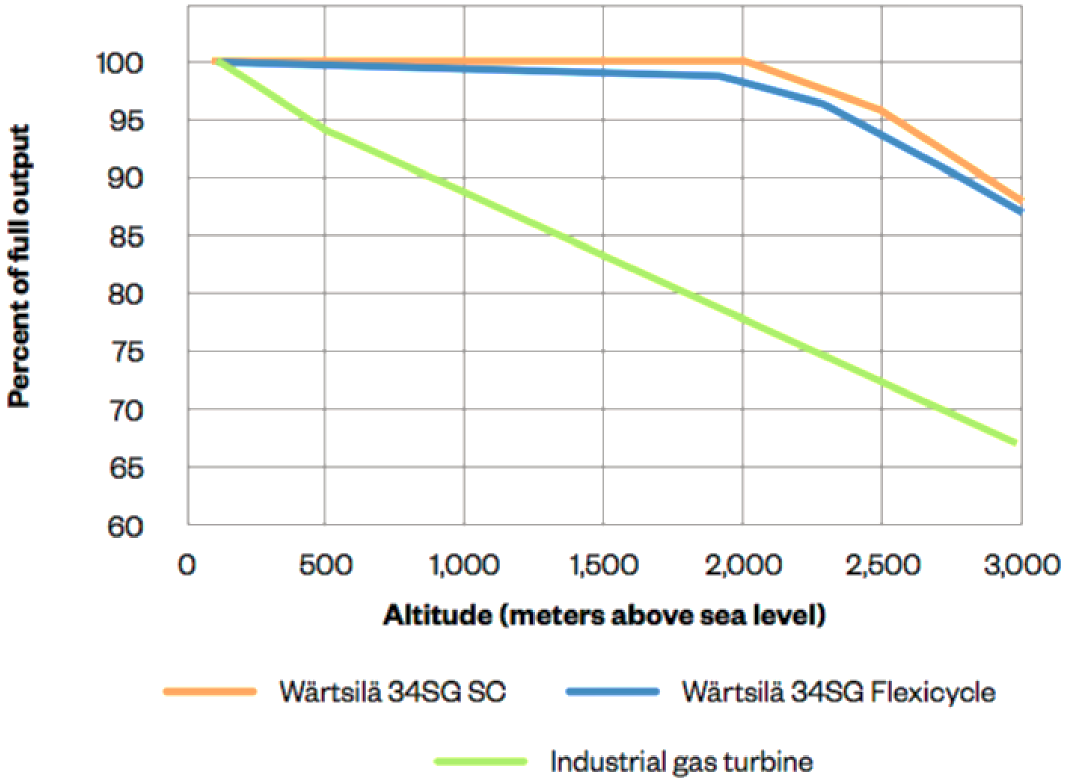


Figure 3-6: Influence of altitude on performance [60]

3.3.16 Influence of temperature on performance

The power output of gas turbines is dependent on the mass flow through the compressor. The density of air decreases at higher temperatures and more power is necessary to compress the same mass of air than at lower temperatures. As a result, the output and the efficiency of gas turbines decrease. There are various techniques to cool inlet air and boost turbine output like evaporative coolers and mechanical chillers. Nonetheless, inlet air-cooling requires additional power and the efficiency of the different cooling systems is strongly depending on the ambient humidity. Gas engines are normally less sensitive to humidity and temperature securing their power output and efficiency over a broader range than gas turbines. While operating at partial load the ambient temperature results in an even greater influence on the efficiency of gas turbines and gas engines. [60][67]

Performance decreases of SOFC systems at higher ambient temperatures are again a result of losses in blower efficiency. [44]

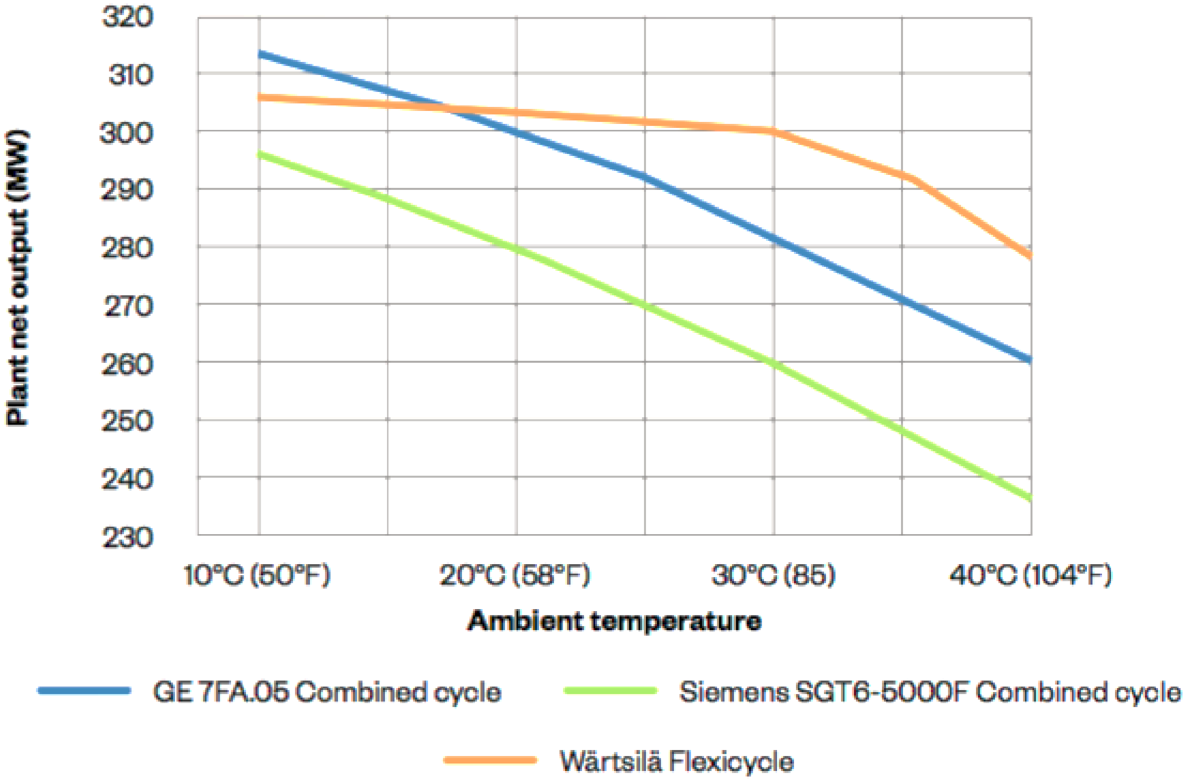


Figure 3-7: Influence of temperature on plant net output [60]

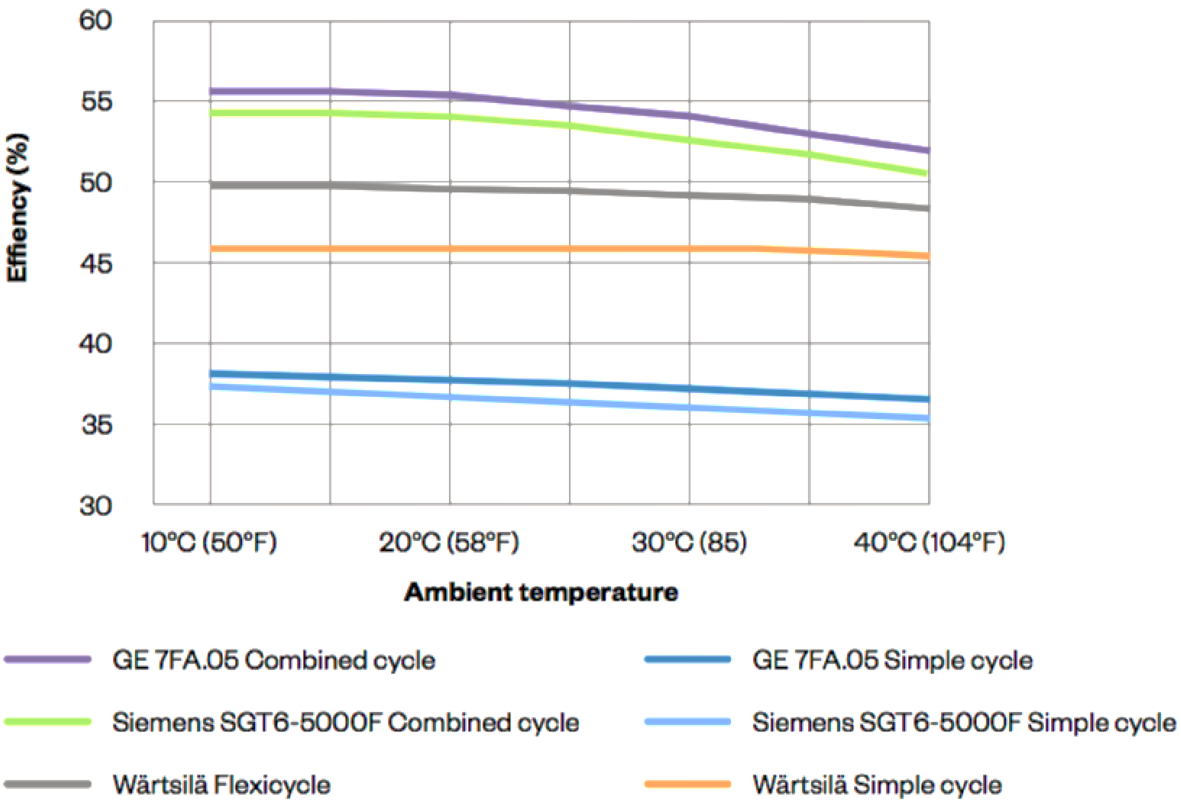


Figure 3-8: Influence of temperature on efficiency [60]

3.3.17 Water consumption

There is no water demand during operation for SOFC systems with hot anode gas recirculation. Water is only needed during start-up and shutdown. The total required water for this system configuration can be calculated with 13 liters per hour and MW. Single pass system configurations (water is needed continuously throughout operation) need approximately 260 liters per hour and MW. It is possible to collect water by exhaust gas condensation if a low temperature level is available. Nevertheless, water consumption is targeted to be minimal to keep efforts for water treatment low. The water consumption of gas turbines and gas engines is negligibly low due to of closed circuit cooling systems. [50][66][68]

3.3.18 Emissions

The SOFC process has no thermal combustion only catalytic combustion of CO and H_2 in the afterburner. Therefore, practically no NO_x is built. Since any sulfur from the fuel must be removed before system entry no SO_x is built. The only noise within SOFC systems is produced by the blowers, which can be quieted easily by reasonable means. Therefore, the emissions are mostly much lower than for gas turbines or gas engines. The CO_2 emissions given in the table below are based on the specific electrical efficiencies of the systems from

53 – 60 % (SOFC), 35 – 37 % (Gas turbine) and 35 – 40 % (Gas engine). The SOFC system CO_2 emissions can reduce further to 234 g/kWh_{CHP} with heat recovery at 53% electrical efficiency. [44][70]

Table 3-15: Emissions

Emissions	SOFC	Gas turbine	Gas engine
CO [g/kWh_{el}]	**0,004**	**0,220**	**1,000 – 2,000**
	[70]	[70]	[70-71]
NO_X [g/kWh_{el}]	**0 – 0,021**	**0,140 – 1,800**	**1,000 – 12,700**
	[1][38][70]	[1][38][70]	[1][38][70]
SO_X [g/kWh_{el}]	**0 – 0,005**	**0,006**	**0,006**
	[70]	[70]	[70]
PM10 [g/kWh_{el}]	**0**	**0,001 – 0,061**	**0,001 - 0,189**
	[69]	[70][72]	[70][72]
CO_2 [g/kWh_{el}]	**328 – 354**	**489 – 610**	**500 – 600**
	[69-70]	[73-74]	[74]
Noise [dB(A)]	**65 – 70**	**85**	**95 – 123**
	[69]	[75]	[5][47]

Table 3-16 illustrates the tradeoffs between NO_x emissions control and efficiency of a gas engine. It can be seen, that at the lowest NO_x levels almost 1,5 % of the maximum electrical efficiency is lost. [76]

Table 3-16: Uncontrolled NO_X emissions vs. efficiency tradeoff [82]

Engine Characteristics	Low NO_X	High Efficiency
Capacity [MW]	9,3	9,3
Efficiency [%]	44,1	45,7
NO_X [% of max. NO_X]	52	100

3.3.19 Availability

The availability of power generating systems strongly depends on the specific application and operational mode. The considered application and operational mode is continuous electricity generation without non-planned maintenance. There is no particular service need to turn off the SOFC system on a yearly basis. Expected downtime periods will be discussed in the next chapter. (100 % Availability = 8760 oph/year)

Table 3-17: Availability

SOFC	Gas turbine	Gas engine
90 – 100 %/year	90 – 98 %/year	92 – 97 %/year
[51-52]	[30]	[30]

3.3.20 Maintenance

3.3.20.1 Maintenance efforts - SOFC

The current lifetime of SOFC stacks is in the range of 20.000 – 40.000 h. Auxiliary system components like heat exchangers and blowers have not been utterly tested so far especially for the large power outputs. Consumable materials such as absorbent and catalysts will be replaced during planned downtime. The main downtime per year for system cool-down and heat-up is calculated with 3 – 4 days in total. [44]

3.3.20.2 Maintenance efforts – Gas turbine

Routine inspections of gas turbines are required every 4.000 oph to assure the gas turbine is free of unreasonable vibration as a result of worn out blade tips or bearings. Additionally inspections of the hot gas path and non-destructive component testing are normally included. The major overhaul typically consists out of a complete inspection and rebuild of various components to restore the gas turbine to original or upgraded performance standards. The maintenance intervals largely depend on utilized fuels, engine size, number of (fast) start-ups, operating temperatures / pressures, operating hours as well as component degradation. [77-78]

Table 3-18: Expected maintenance efforts - Gas turbine [77-78]

Service	Interval [oph]	Overhauled components	Estimated downtime
Standby inspections	regularly	Changing filters, checking oil and water levels, cleaning relays,…	-
Combustion inspection	8.000 – 12.000	**Inspect/repair/refurbishment/replace:** Combustion chamber components, crossfire tube, retainer and combustion liner, combustion system and discharge casing, flow sleeve, transition piece, fuel nozzles, impingement sleeves, all fluid, air, gas passages in nozzle assembly, spark plug assembly, electrodes and insulators, first-stage turbine nozzle partitions, turbine buckets, compressor, consumables and normal wear-and-tear items such as seals, lockplates, nuts, bolts, gaskets,...	10 days
Hot gas path inspection	24.000	**Inspect/repair/refurbishment/replace:** First-, second-, and third-stage buckets and nozzles, seals, hook fits of turbine nozzles and diaphragms, later-stage nozzle diaphragm packings, discourager seals, bucket tips, bucket shank, cutter teeth of tip-shrouded buckets, turbine stationary shrouds, turbine rotor, wheelspace thermocouples, compressor, turbine shell shroud hooks,...	45 days
Major overhaul	48.000	**Inspect/repair/refurbishment/replace:** Full compressor system, unit rotor, journals and seal surfaces, bearing seals, exhaust system, interior/exterior cases,...	45 – 60 days

3.3.20.3 Maintenance efforts – Gas engine

The maintenance of gas engines can be performed either by internal personnel or under service contracts with the manufacturers or distributors. Full service contracts often include remote monitoring of the engine performance to allow predictive maintenance. These maintenance contracts cover all recommended service and normally cost 0,7 – 1,4 cents/kWh. The maintenance intervals largely depend on utilized fuels, engine size, speed as well as degradation of single components. [74][79]

Table 3-19: Expected maintenance efforts – Gas engine [4][38][80-82]

Service	Interval [oph]	Overhauled components	Estimated downtime
Minor / Top-end overhaul	500 – 2.000	**Inspect/repair/refurbishment/replace:** Spark plugs, filters consumeables/fluids, valve adjustement,...	5 – 11 hours
Minor / Top-end overhaul	8.000 – 12.000	**Inspect/repair/refurbishment/replace:** Spark plugs, turbo charger, pre-chamber, gas mixer, pumps,...	1 – 4 days
Minor Overhaul	24.000 – 45.000	**Refurbished Components:** Cam follower, actuator and throttle valve, crankcase with covers, crankshaft, connecting rods, cylinder heads, geardrive, mixture intake manifold (up to throttle valve), oil cooler, pipes and oil pressure regulation valve, oil pump, oil sump, valve control and control covers, water pump, brackets for engine lifting device, transport frame,... **New Components:** Cylinder heads and liners, knocking sensors, pistons, piston cooling nozzles, camshaft, camshaft pickup, main bearing and con rod bearings, oil filter, vibration damper with protection, painting,...	< 11 days
Major Overhaul	45.000 – 80.000		1 – 3 weeks

3.3.20.4 Major overhaul interval

The operating hours between major overhaul may vary widely with system configuration, operational mode, application, fuel, and service contract. [1][38][44][79-80][83]

Table 3-20: Major overhaul interval

	SOFC	**Gas turbine**	**Gas engine**
Oph between major overhauls	10.000 – 40.000	25.000 – 50.000	24.000 – 80.000
	[1][44]	[38][77]	[38][6][79-80]

3.3.21 Cost analysis

A comparison of the total plant costs of grid-interconnected CHP applications are given in the *Table 3-21.*

Table 3-21: Total plant costs of grid-interconnected CHP applications

Power output	**SOFC**	**Gas turbine**	**Gas engine**
1 MW	1.900 – 2.400 €/kW	1.910 €/kW	940 €/kW
5 MW	-	1.024 €/kW	892 €/kW
10 MW	-	928 €/kW	-
	[84]	[4]	[4]

All estimates are based on elementary installation requirements with minimal site preparation. The mainly considered application is the supply of electrical base load. The costs are based on popular gas engines like Caterpillar G3616, Coast Intelligen Model 150-IC, Cummins QSV91G and GSK19G, various MAN engines and Wärtsilä 18V34SG and have been compared with price ranges presented in other publications. Estimates of the future performances include cost changes and improvements in terms of efficiency, emissions, electrical equipment and other systems costs as well as engineering, project / construction and management and project contingencies as well as market changes. [4][38][55][76][84]

Table 3-22: Total plant costs of grid-interconnected CHP applications – Gas engine [4]

	Gas engine
Nominal Output [MW]	**1**
Genset Package [€/kW]	370
Heat Recovery [€/kW]	90
Interconnect/Electrical [€/kW]	100
Total Equipment Costs [€/kW]	**560**
Labor/Materials [€/kW] (45 % of Total Equipment Costs)	240
Total Process Capital [€/kW]	**800**
Project/Construction & Management [€/kW] (10 % of Total Equipment Costs)	56
Engineering & Fees [€/kW] (9% of Total Equipment Costs)	56
Project Contingency [€/kW] (5% of Total Equipment Costs)	28
Total Plant Costs [€/kW]	**940**
Total Plant Costs Projection 2030 [€/kW]	800

The cost estimates for gas turbines include dry low emissions control, HRSG, compression, treatment of the boiler water, utility interconnection for parallel power generation as well as minimal site preparation and are based on 90 turbine generator sets smaller than 50 MW. Estimates of the future performances include cost changes and improvements in terms of efficiency, NO_x emissions, electrical equipment and other systems costs as well as engineering, project / construction and management and project contingencies as well as market changes. [4][38][85-86]

Table 3-23: Total plant costs of grid-interconnected CHP applications – Gas turbine [4]

	Gas turbine
Nominal Output [MW]	**1**
Combustion Turbine [€/kW]	660
HRSG [€/kW]	425
Water Treatment System [€/kW]	25
Electrical Equipment [€/kW]	125
Other Equipment (Compressor…) [€/kW]	120
Total Equipment Costs [€/kW]	**1.175**
Labor/Materials [€/kW] (35 % of Total Equipment Costs)	476
Total Process Capital [€/kW]	**1.651**
Project/Construction & Management [€/kW] (10 % of Total Equipment Costs)	118
Engineering & Fees [€/kW] (6% of Total Equipment Costs)	82
Project Contingency [€/kW] (5% of Total Equipment Costs)	59
Total Plant Costs [€/kW]	**1.910**
Total Plant Costs – 5 MW [€/kW]	1.024
Total Plant Costs – 10 MW [€/kW]	928
Total Plant Costs – 5 MW Projection 2030 [€/kW]	810
Total Plant Costs – 10 MW Projection 2030 [€/kW]	760

The SOFC systems costs per kW are assumptions by AVL List GmbH based on the cost distribution of the conventional technologies. Costs may vary widely for different stack manufacturers. [44]

Table 3-24: Total plant costs of grid-interconnected CHP applications – SOFC [44]

	SOFC
Nominal Output [MW]	**1**
CAPEX SOFC Stack [€/kW]	1.000
CAPEX BoP [€/kW]	1.000
Total Equipment Costs [€/kW]	**2.000**
CAPEX Overhead [€/kW]	400
Total Plant Costs [€/kW]	**2.400**

3.3.21.1 O&M costs

The typical distribution of the operation and maintenance costs for conventional gas-fired power distribution technologies is presented in the chart below. The costs refer to a 2 MW gas engine, 8.000 oph per year over 10 years of operation. Fuel costs are calculated at 0,145 cent/kWh and oil costs at 20 $/US gallon. [87]

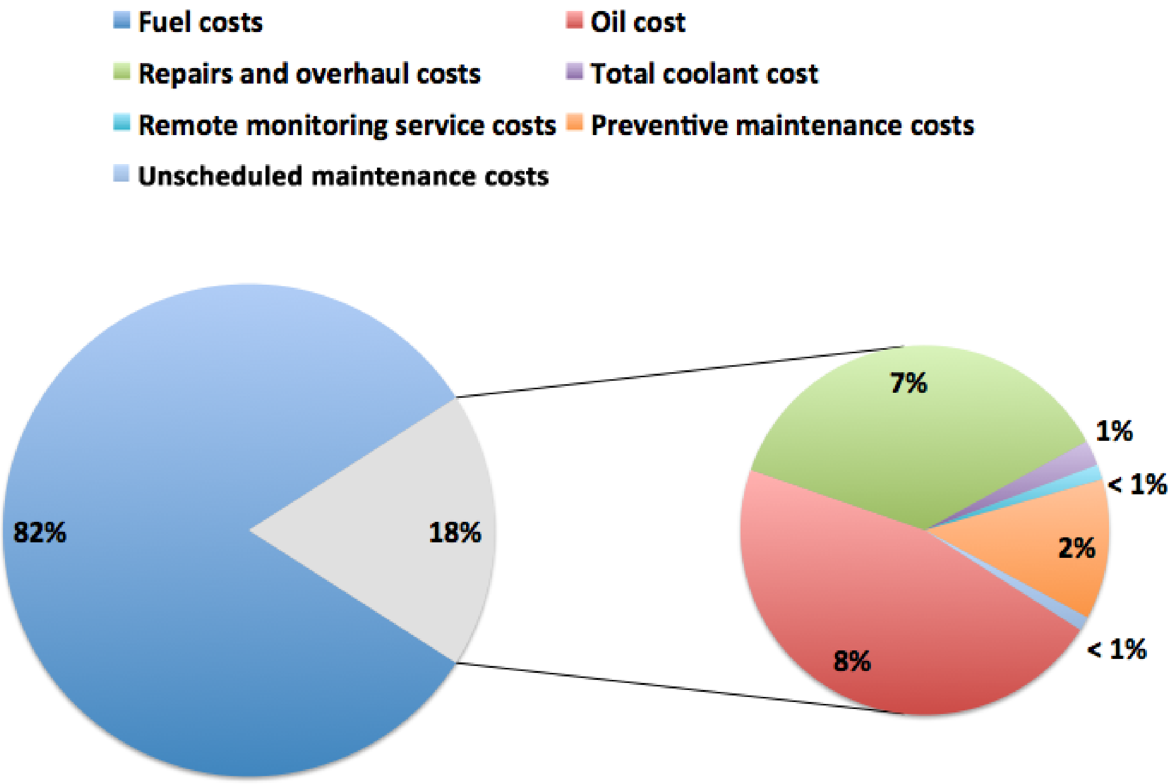


Figure 3-9: O&M costs distribution [95]

The following maintenance costs present the estimates for service contracts of various engine manufacturers. This full service contracts include routine inspections and scheduled overhaul of gas engines and gas turbines, excluding fuel costs. The costs are based on 8.000 hours of annual electricity generation over a period of 20 years Additional preventive maintenance procedures that are able to detect trends in performance or fuel consumption are part of all service contracts. [4]

Table 3-25: Maintenance costs: Gas turbine vs. Gas engine [4]

	Gas turbine	**Gas engine**
Nominal Output [MW]	**5**	**5**
Variable (Service Contract) [$/kWh]	0,0045	0,0079
Variable (Consumables) [$/kWh]	0,0001	-
Fixed [$/kW-yr]	10,0	1,1
Fixed (8000 h/year) [$/kWh]	0,0013	0,00014
Total O&M Costs [$/kWh]	**0,0059**	**0,008**

Details of maintenance contracts for SOFCs are generally not available. The maintenance costs of the SOFC are estimated at 0,7 – 2,0 cents/kWh compared to the 0,7 – 1,4 cents/kWh of gas engines. The sinking fund for the cost of replacing the stack is also not included. The initial stack cost is calculated at 1000 $/kW and the cost for replacement of the stack at > 50 % of the total SOFC maintenance costs. All estimates should take a cost variety of +/- 15 % into account as a result of stack price changes. [4][85][86]

Table 3-26: Maintenance costs: SOFC vs. Gas engine [4]

	SOFC	**Gas engine**
Nominal Output [kW]	**100**	**100**
Variable (Service Contract) [$/kWh]	0,0102	0,017
Variable (Consumables) [$/kWh]	0,0002	-
Fixed [$/kW-yr]	10	10
Fixed (8000 h/year) [$/kWh]	0,0013	0,00125
Stack Fund [$/kWh]	0,0125	-
Stack life target [years]	8	-
Stack recovery factor [%]	20	-
Total O&M Costs [$/kWh]	**0,024**	**0,018**

Table 3-27: Comparison of maintenance costs [4]

Power output	SOFC	Gas turbine	Gas engine
100 kW	0,0240 $/kWh	-	0,0180 $/kWh
0,8 – 1 MW	-	0,0096 $/kWh	0,0090 $/kWh
5 MW	-	0,0059 $/kWh	0,0080 $/kWh
> 85 MW (Plant)	-	0,0044 $/kWh	0,0067 $/kWh

Table 3-28: Maintenanmce costs projection 2030 [4]

Power output	SOFC	Gas turbine	Gas engine
100 kW	0,0130 $/kWh	-	0,0100 $/kWh
5 MW	-	0,0050 $/kWh	0,0078 $/kWh

3.3.22 Market overview and developments

3.3.22.1 Applications of gas turbines and gas engines

Conventional CHP systems based on gas turbines and gas engines produced by numerous manufactures have established a broad range of applications over the last century. The charts below show typical distribution of applications for gas engines and gas turbines based on data from the United States of America. [4]

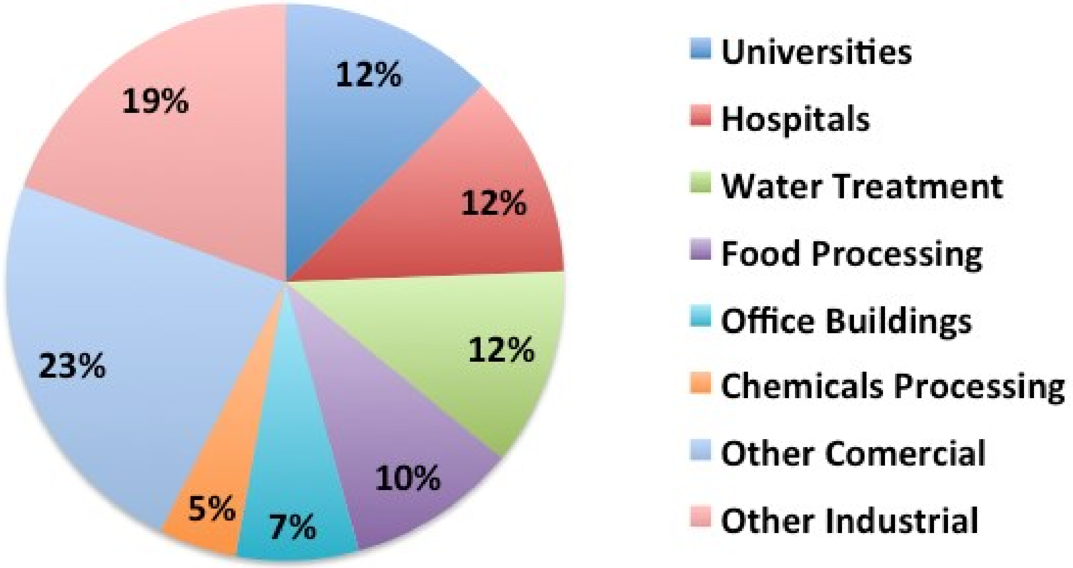


Figure 4-10: Existing large engine CHP - 801 MW at 1.055 sites [4]

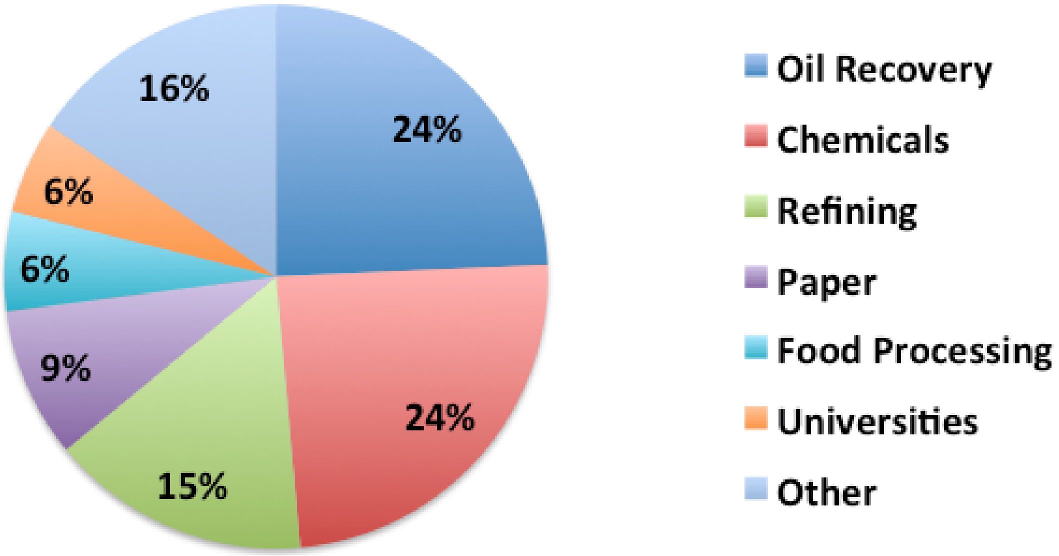


Figure 4-11: Existing simple cycle gas turbine CHP – 9.854 MW at 359 sites [4]

3.3.22.2 Applications of the SOFC

Commercial SOFC CHP systems are available from different manufacturers like Kyocera Aisin Seiki, Bloom Energy, Fuel Cell Energy, SOLIDpower and Convion. Nevertheless, the technology is still far behind other available CHP technologies. The current main applications are commercial and industrial CHP (200 – 2800 kW), pure electrical generation (105 – 210 kW), residential and commercial systems for CHP (3 – 10 kW), back-up and portable power systems (0.25 – 5 kW). Recently integrated SOFC systems are used to power data centers. [1][44][70][83]

3.3.22.3 Gas market

In the global energy landscape a growth in natural gas production and consumption as well as an expansion of networks is expected. As a result, this will lead to direct competition of natural gas with coal and oil and supports various renewable energy sources. It can be expected, that natural gas production will increase by 35 % from 2012 to 2025, from 3.518 to 4.780 billion cubic meters. There are also strong fluctuations in the gas price that must be taken in account. [83][89-90]

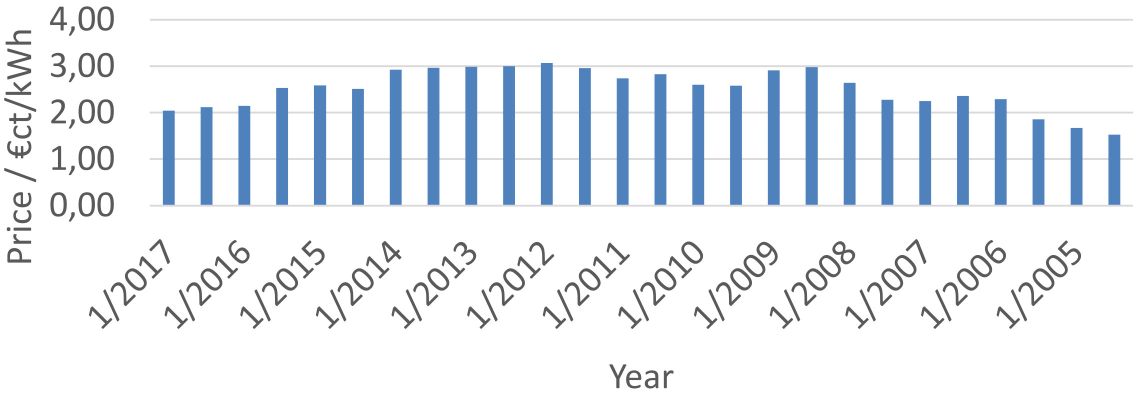


Figure 3-12: Natural gas price [89]

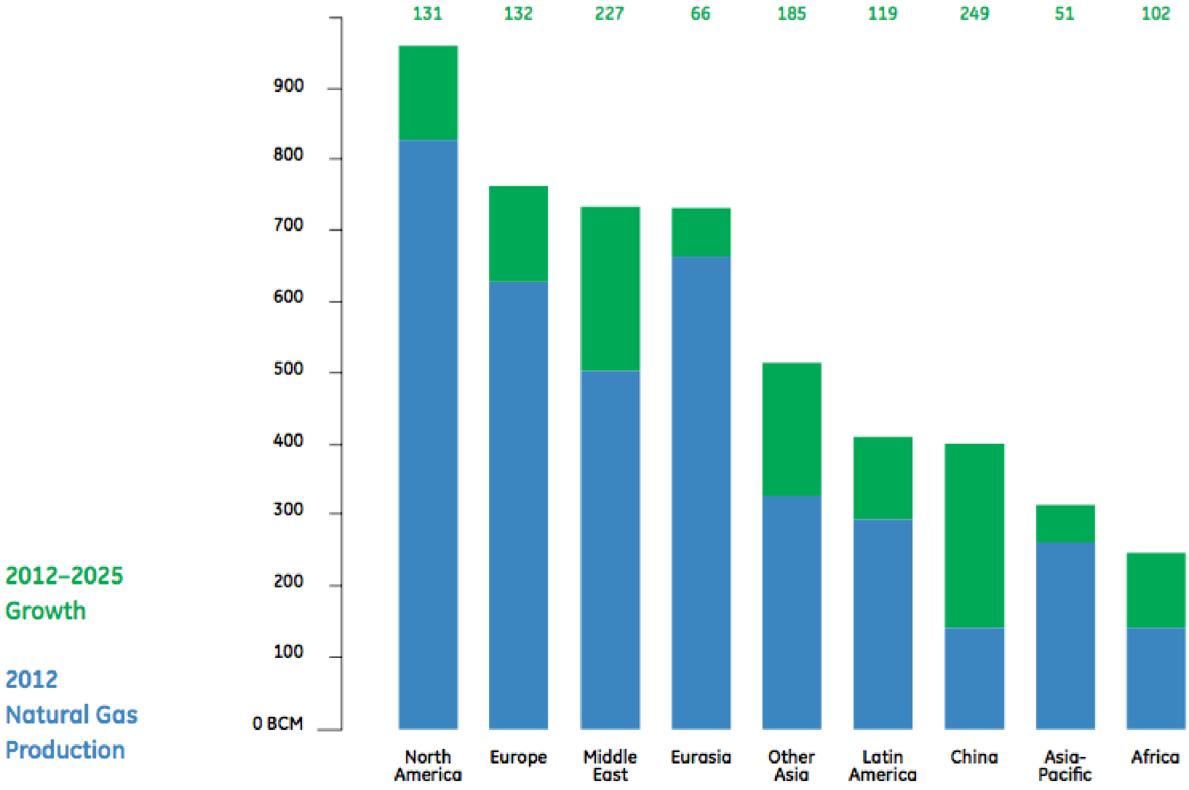


Figure 3-13: Natural gas production and growth [90]

3.3.23 Applications

The *Table 3-29* represents a compact comparison of different operation types for conventional power plants. The assumptions regarding the full load operating hours per year were compiled during meetings with various experts from the AVL List GmbH.

Table 3-29: Applications

Operation type	Description	Full load oph / year	Plant owner / Operator	Application
Continuous power only	Steady state operation Electricity controlled	6.000 – 8.000 h	Utility	For example: Power plant for grid feed in
Continuous CHP	Steady state operation Heat controlled	6.000 – 8.000 h	Utility	For example: District heating
Prime	Own consumption Optional: Grid feed-in	~ 5.000 h	IPP	For example: Steel plant
Island	Own consumption Load following Electrical buffer storage	> 8.000 h	IPP	For example: Remote applications
Backup / Standby	Fast start-up Load following Electrical buffer storage	~ 200 h	Application owner	For example: Hospital
Control energy	Balancing grid generation vs. demand Grid frequency control Grid power balancing Fast ramp-up/down	-	Utility IPP	For example: Grid balancing

[5][70][91-94]

4 MODEL DEVELOPMENT

The overall aim of this project is to compile a model, which represents the behavior of SOFCs to specify the suitability of the technology for different applications. The results of the simulation are combined with the technical and economical comparison of SOFCs with conventional reference technologies, in order to determine the requirements for SOFC CHP systems as controllable power plants of the future.

4.1 Aims and structure of the model

The aim of the model is to determine optimal SOFC CHP system configurations and operational modes for specific applications with load profiles as input parameter. The model was designed in MathWorks MATLAB and consists out of multiple scripts and functions. Furthermore the model package includes several Microsoft Excel sheets that interact with the code in a way to enable calibration of the model by high dynamic process analysis. The model is structured in more than 20 fully commented segments to ensure transparency and enable easy adaptation of single parts of the code – tailor-made for specific applications.

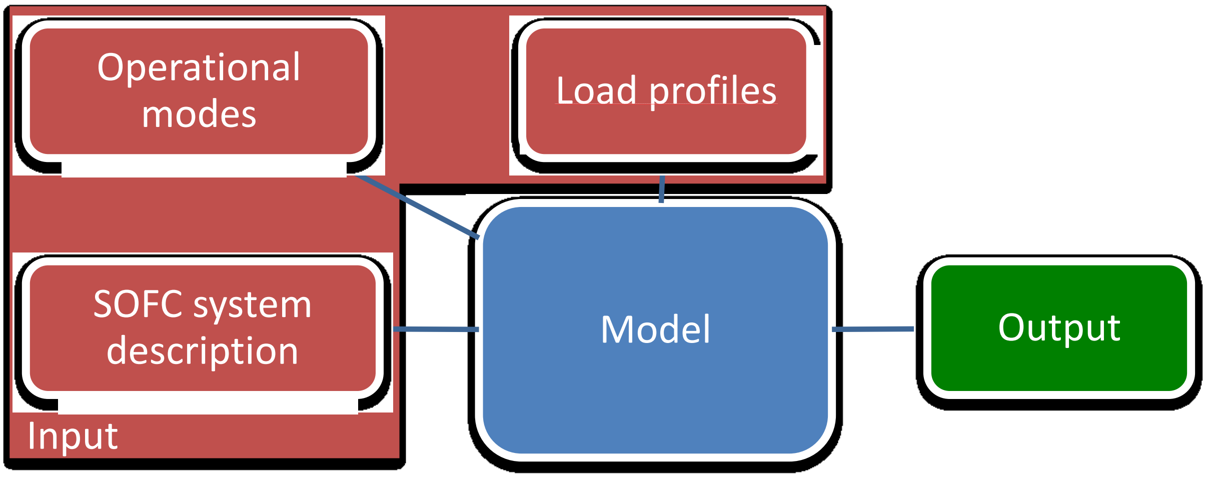


Figure 4-14: Model structure

4.2 Model assumptions

The input of the model consists out of the three parts. The first part, the SOFC system description is defined by following parameters:

Nominal parameters

- Nominal electrical power output of the system ($P_{el,n}$)
- Electrical, thermal and total efficiency
- Ramp-up and ramp-down rates
- Temperature heat-up / cool down values (dT)

Operating limits

- Starting value: Partial load point / Full load point (x_{Start})
- Minimum value of the partial load point (x_{min})
- Maximum value of the partial load point (x_{max})
- Maximum possible part load point at specific system temperature ($x_{p,max}$)
- Starting value: System temperature (T_{Start})
- Maximum system temperature (T_{max})
- Self-adjusting temperature at specific part load point (T_{self})

Controlling parameters

- Dynamic or static behavior of the system / Load-followability (d./s.)
- Set-point setting and system priority (when simulating multiple systems)

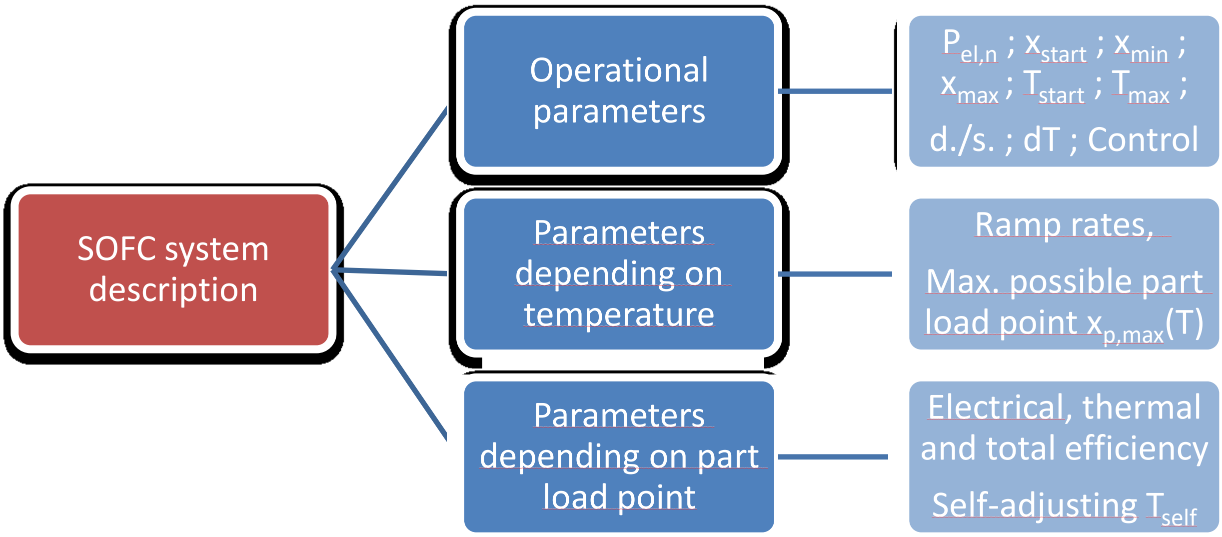


Figure 4-15: Model structure - SOFC system configuration

Various dependencies of system related parameters like electrical efficiency, total efficiency, ramp-up rate, ramp-down rate, maximum partial load points at specific temperatures and temperature heat-up / cool down values can be defined and modified in the additional provided Excel sheets. Specific values will then be approximated in the model by linear interpolation.

Table 4-30: System parameters

Part load point [% of full power]	**Electrical efficiency [%]**	**Total efficiency [%]**	**Self-adjusting minimal temperature [°C]**
0	0	0	720
50	62	90	780
100	57	90	830
Temperature [°C]	**Ramp-up rate [% of nominal power / minute]**	**Ramp-down rate [% of nominal power / minute]**	**Maximum possible part load point [%]**
< 720	0	0	0
720	3	200	50
800	100	200	75
830	100	200	100

The temperature behavior of the systems works in a way that a ramp-up of power basically leads to a raise in temperature while ramping-down power results in a temperature drop.

Furthermore, the following rules are applied:

- The temperature cannot exceed the maximum stack temperature
- A ramp-down in power in the partial load range of 100% to 75% power will not cause a temperature drop
- Below 50% load the system is not thermally self-sustaining, therefore operation between 0 – 50% will cause major electrical efficiency drops as a result of additional burner operation

The second and third part of the input are the load profiles and the operational mode. The load profile input are an electrical and a thermal load profile over a specific time range. The two different operational modes of the model are the electricity-controlled mode, which follows the electrical load profile and the heat-controlled mode, which adjusts the electricity production in order to follow the thermal load profile.

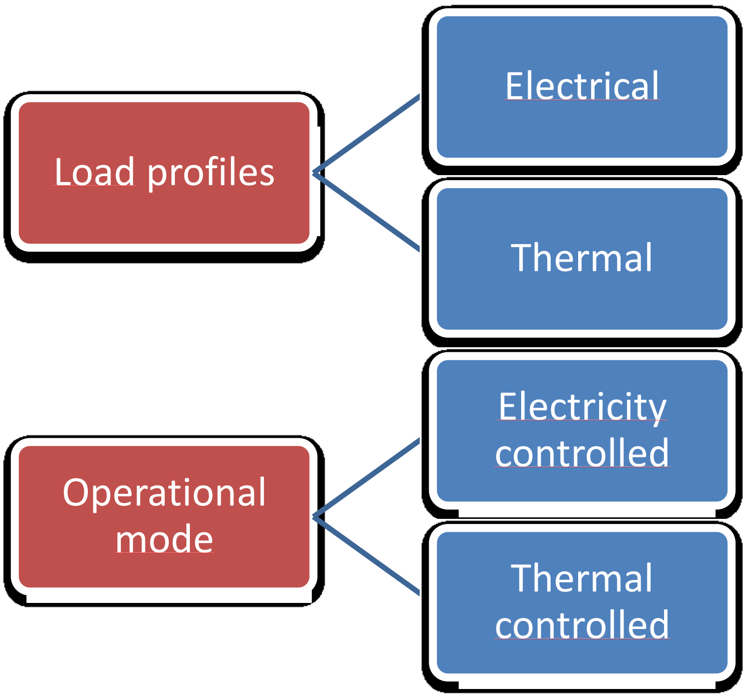


Figure 4-16: Model structure – Load profiles and operational mode

The load following function of the model simply compares the power set-point value with the current power output of the system and tries to readjust – considering all restrictions due to defined system input parameters. The results are the actual reachable value as well as the corresponding system status.

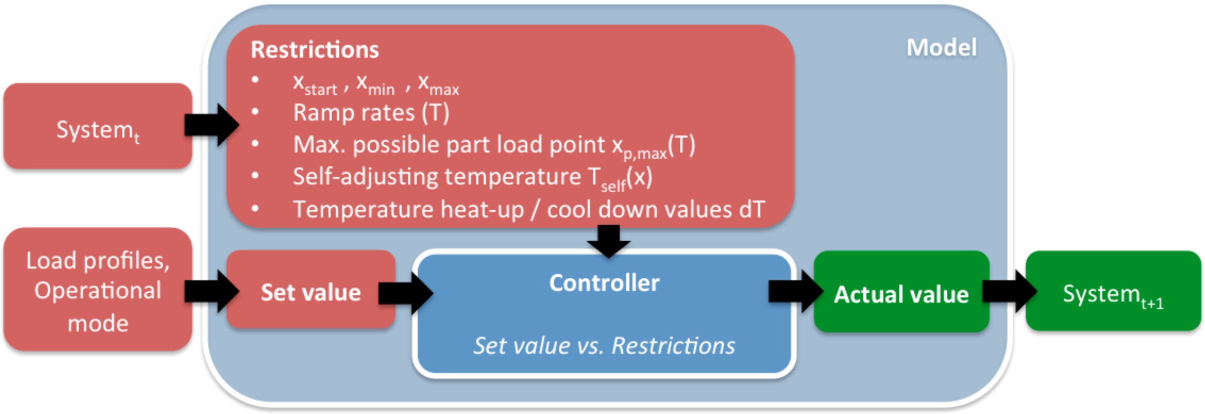


Figure 4-17: Model structure – Load following function

In detail, the model works in a way that the electrical set value of the load profile $P_{el,set}$ is compared to the current power output $P_{el,0}$ of the SOFC system. In order to follow the load profile one of the following three ramping operations is conducted.

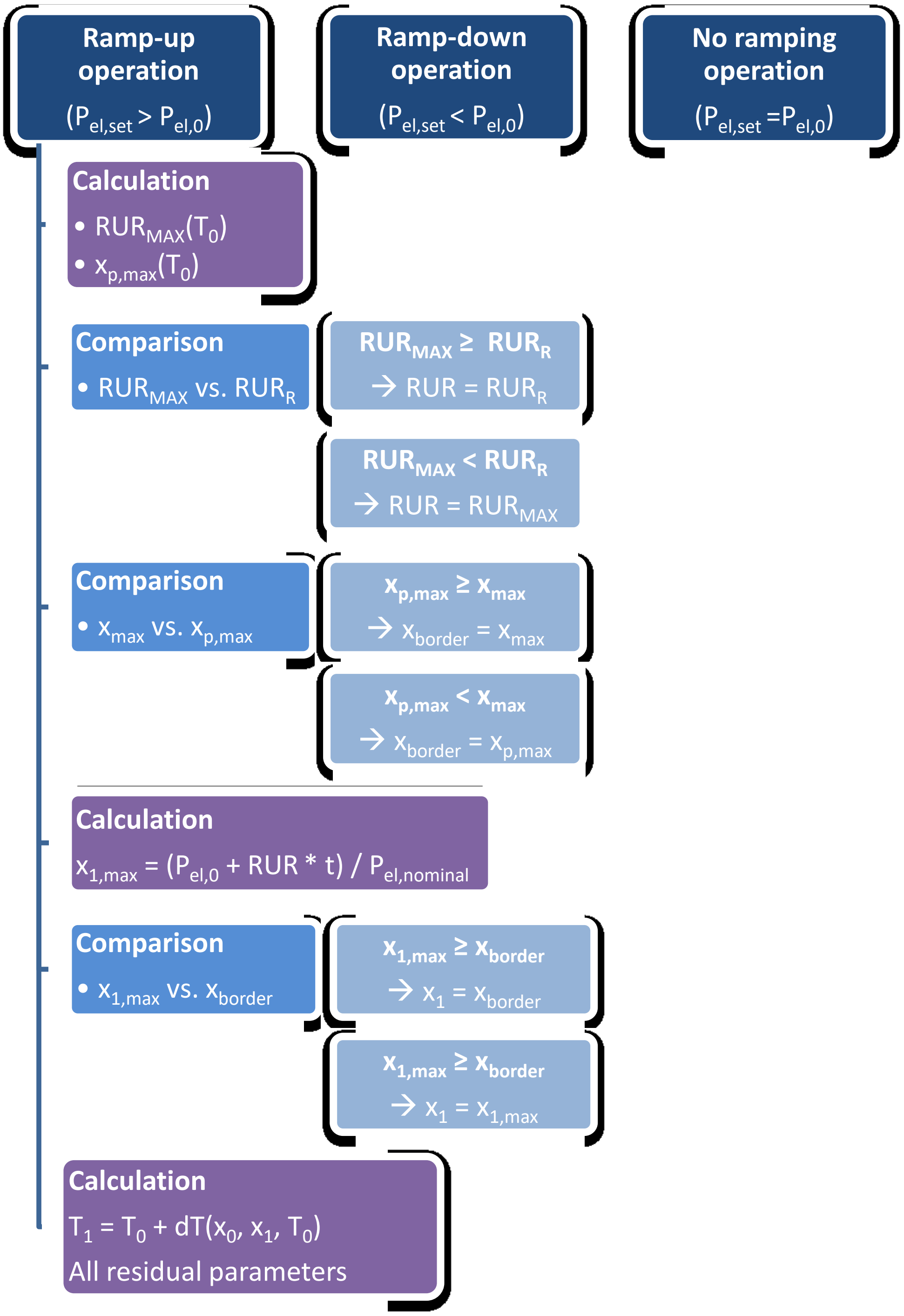


Figure 4-18: Ramping operations

Description of the ramp-up operation:

- Calculation of the maximum possible ramp-up rate RUR_{MAX}, depending on the current stack temperature T_0, by interpolation with data provided in the Excel sheets.
- Calculation of the maximum possible part load point $x_{p,max}(T_0)$, by interpolation with data provided by the Excel sheets.
- Comparison of the maximum possible ramp-up rate RUR_{MAX} with the required ramp-up rate RUR_R in order to follow the load profile. Determination of the actual ramp-up rate RUR.
- Comparison of the maximum allowed part load point x_{max} which is defined by the operational mode and the maximal possible part load point $x_{p,max}(T_0)$. Determination of the part load point border x_{border}.
- Calculation of the maximum achievable part load point $x_{1,max}$.
- Comparison of maximal achievable part load point $x_{1,max}$ with the part load point border x_{border}. Determination of the new part load point x_1.
- Calculation of the new stack temperature corresponding to data provided in the Excel sheets and all residual parameters given in the lists and figures of this chapter.

The ramp-down operation ($P_{el,set} < P_{el,0}$) works similar to the ramp-up procedure except the usage of the ramp-down rate and the minimum achievable part load point ($x_{1,min} = (P_{el,0} - RDR * t) / P_{el,nominal}$). Furthermore the maximum possible part load point has no influence ($x_{border} = x_{min}$). The stack temperature decreases with consideration of the limits given by the minimal self-adjusting temperature at a specific part load point $T_{self}(x)$.

The outputs of the model are the following parameters for every single system or system configuration over the simulated time range:

- Electrical load profile and thermal load profile
- Electrical and thermal power output of the system
- Partial load point
- Electrical, thermal and total efficiency
- Fuel power
- Power to heat ratio
- Ramp-up and ramp down rate
- System temperature
- Remaining amount of electrical, thermal and thermal-baseload power
- Surplus electrical, thermal and thermal-baseload power
- Cover ratio of electrical, thermal and thermal-baseload power
- Annual load duration curve

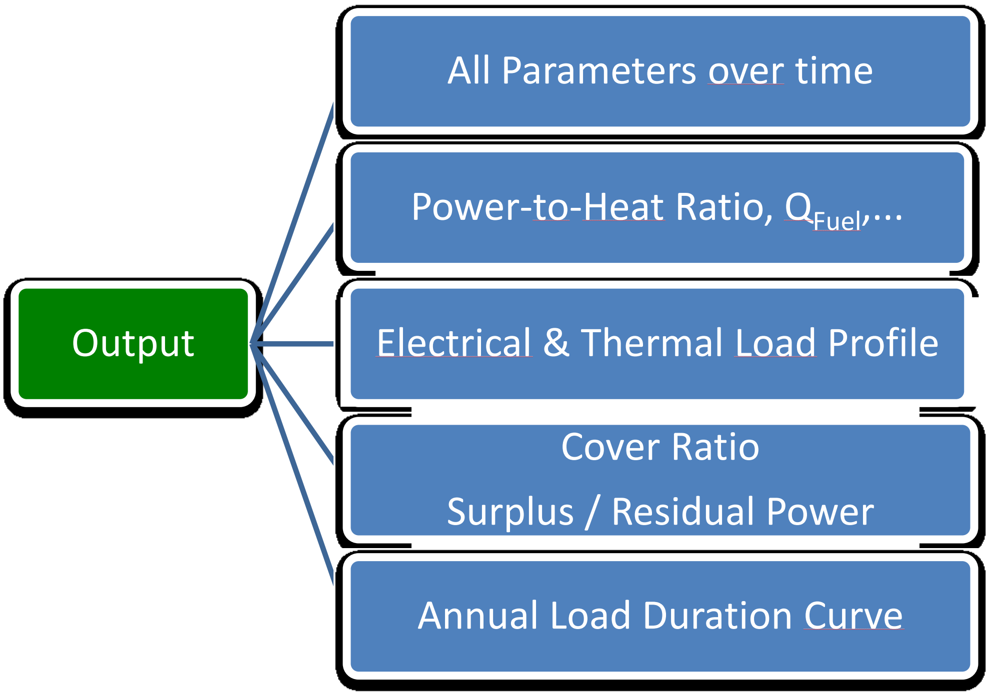


Figure 4-19: Model structure - Output

Furthermore, the model includes an energetic thermal energy storage model that can be operated accordingly to different requirements. It can be distinguished between following the thermal base load or the whole thermal load profile in consideration of the minimal set filling level of the storage. The output data from the storage model can be used as basis for the storage design.

5 CASE STUDIES

In order to verify the functionality of the model, different strategies have been selected. The supply of control energy, the combined production of electricity and heat for industrial and residential applications and the suitability to cover residual loads are simulated for different SOFC system configurations and operational modes.

The applications for the supply of control energy and coverage of residual loads were selected to test the suitability of a SOFC to assist in balancing the grid. These applications require excellent load coverage as well as reliability of power supply. The industrial application tests the suitability of the SOFC to supply electricity and heat in combination optimal cover ratios. Furthermore, different system configurations are tested in order to determine key parameters for industrial operation. The residential application tests the suitability of the SOFC to adapt to seasonal load profile differences by adjusting the power to heat ratio.

The results show various combinations of possible SOFC CHP system configurations to meet the specific requirements as well as the limits of the technology.

5.1 Prequalification of control energy

The technical requirements to distribute control energy in order to assist in balancing the grid include ensuring the follow ability of specific load curves with determined power ramp rates. For primary control the power plant must be connected to the transmission grid, which requires a specific high-power output. In order to supply secondary or tertiary control energy the power plant must be connected to the distribution grid and a smaller nominal power output is sufficient.

In order to pass the prequalification requirements for secondary control, a minimum power ramp rate of 1 MW per minute is necessary for the minimum demanded power supply of 5 MW. Additionally, the supplied power has to be available at all times. [95]

In contemplation of checking the suitability of SOFCs for the supply of control energy the following strategy and the three system configurations CE1, CE2 and CE3 were simulated with the model.

- Strategy: Control Energy:
    - Aim: Fulfill technical prequalification requirements for the distribution of secondary and tertiary control energy regarding ramp rates and reliability of power supply (Ramp rate of 1 MW per minute for the minimum demanded power supply of 5 MW)
    - Operational mode: Electricity controlled
    - Method: Testing of multiple SOFC systems configurations

Table 5-31: System configuration CE1, CE2 and CE3

	System configuration CE1	**System configuration CE2**	**System configuration CE3**
Nominal electrical power [MW]	10	20	35
Control energy power [MW]	5	5	5
Stack temperature [°C]	830	830	830
Operational mode [% load]	50 – 100	75 – 100	33 – 50

System configuration CE1 tests the suitability of a SOFC for the supply of secondary control energy while operating thermally self-sustaining between 50 – 100 % load. System configuration CE2 tests the suitability of a SOFC for the supply of secondary control energy while operating between 75 – 100 % load. A ramp-down in power in this specific partial load range will not cause a temperature drop. System configuration CE3 tests the suitability of a SOFC for the supply of secondary and tertiary control energy while operating thermally non self-sustaining between 33 – 50 % load.

Table 5-32: Results for system configuration CE1

System configuration	**Electrical cover rate [%]**	**Partial load point minimum [% of full load]**	**Self-adjusting minimum temperature [°C]**	**Ramp-up rate at minimum temperature [% of max. power output per minute]**
C1	< 100	50	780	75

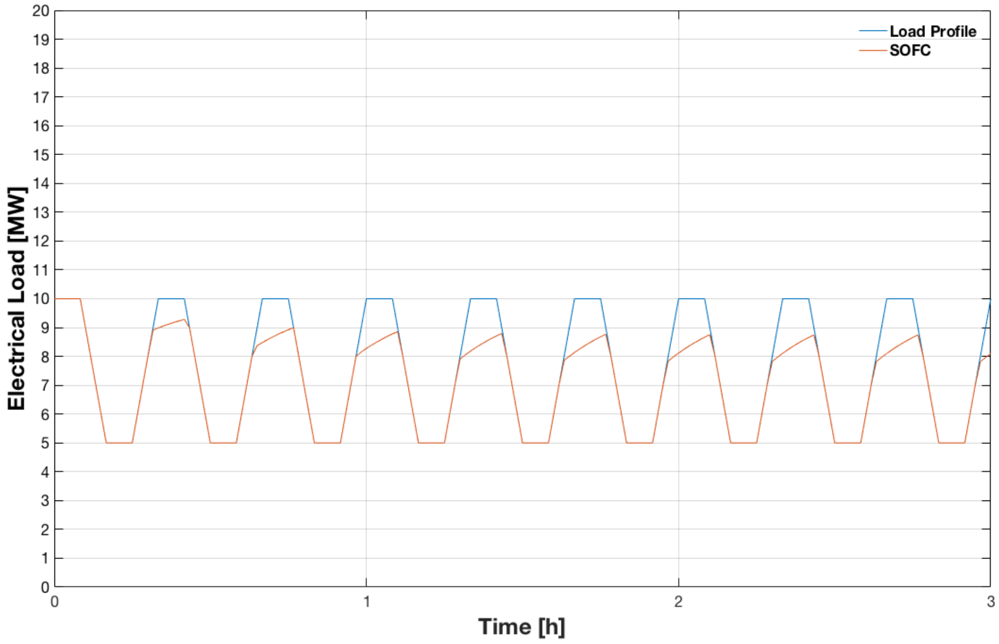


Figure 5-20: System configuration CE1 - Electrical load

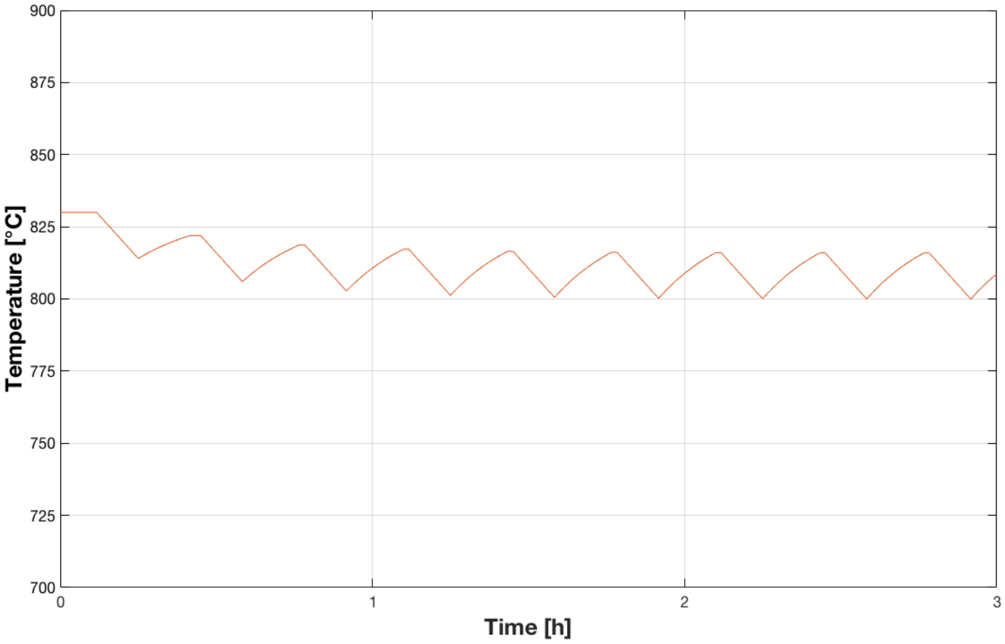


Figure 5-21: System configuration CE1 - Temperature

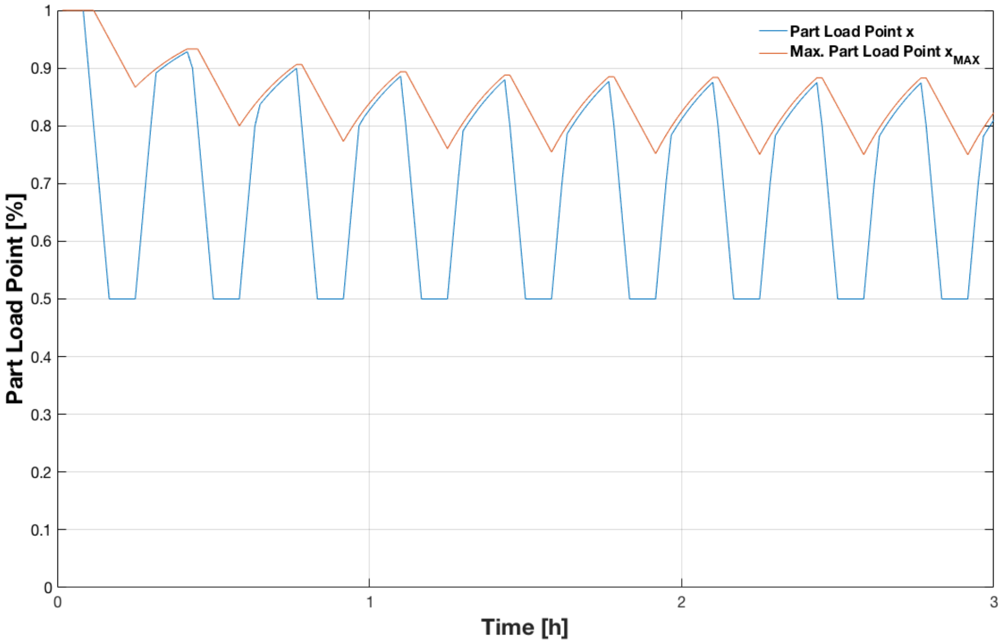


Figure 5-22: System configuration CE1 – Partial load point

As shown in *Figure 5-19* the power ramp rates of system configuration CE1 are high enough to follow the prequalification load profile up to about 90 % of full load.

Above this value the power ramp rate is limited due to a decrease in temperature (*Figure 5-20*), resulting from a starting temperature smaller than the maximal stack temperature of 830 °C at the partial load point of 50 % load. The comparison of the maximum possible partial load point x_{max} to the actual partial load point *x,* depending on the current stack temperature is shown in *Figure 5-21.*

Table 5-33: Results for system configuration CE2

System configuration	Electrical cover rate [%]	Partial load point minimum [% of full load]	Self-adjusting minimum temperature [°C]	Ramp-up rate at minimum temperature [% of max. power output per minute]
C2	100	75	T_{max} = 830	100

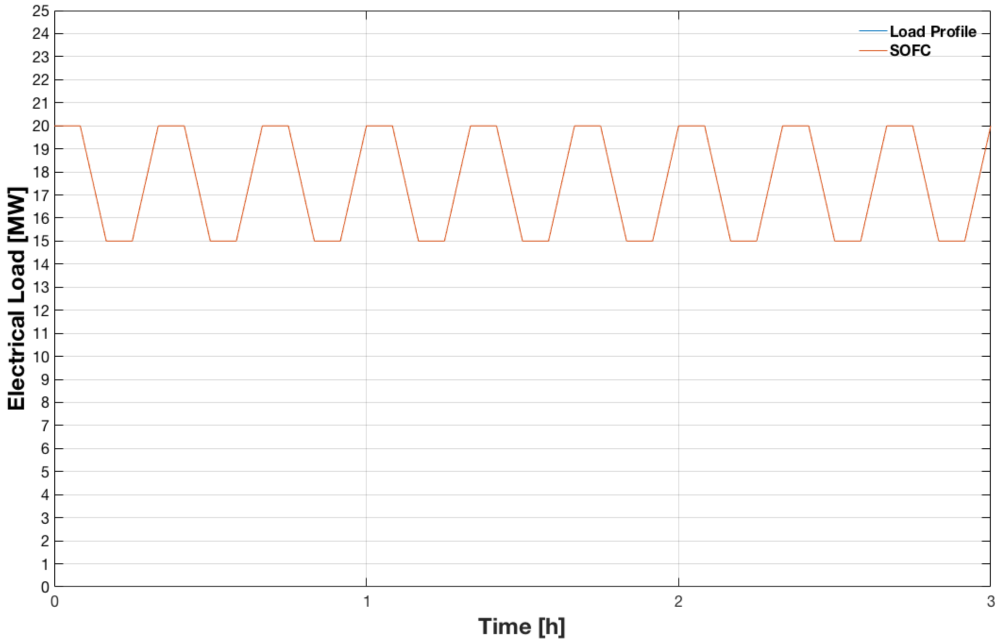


Figure 5-23: System configuration CE2 – Electrical load

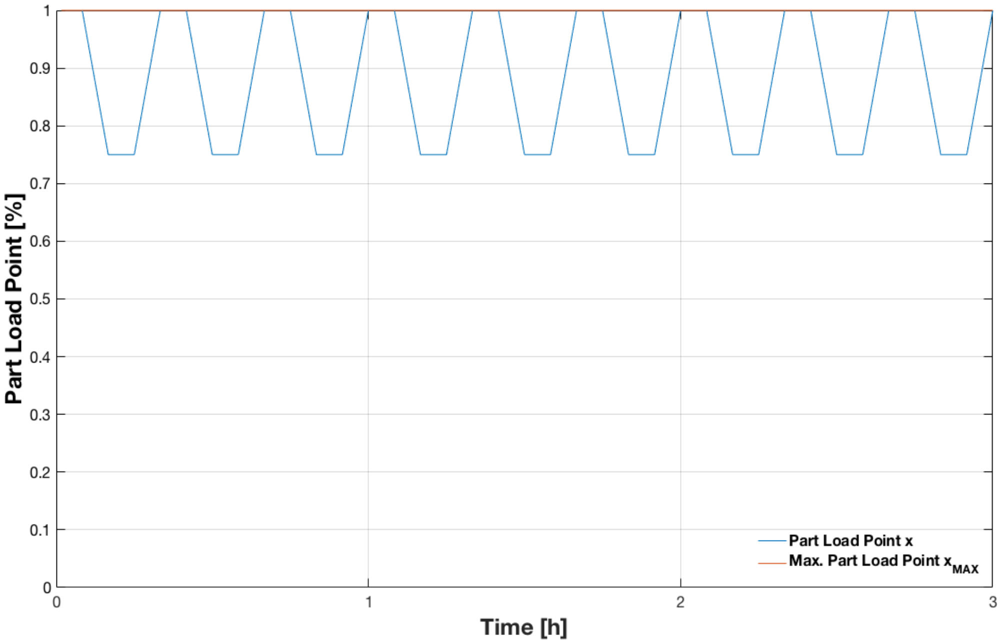


Figure 5-24: System configuration CE2 – Partial load point

System configuration CE2 considers the constant stack temperature while operating between 75 and 100%. Therefore, there is no decrease of temperature during a ramp down while a ramp up still causes a temperature increase. As shown in *Figure 5-23* and *Figure 5-24* the SOFC system configuration CE2 is perfectly able to follow the prequalification requirements for secondary and therefore also tertiary control energy. As a result, it is shown that in order to provide a specific power ramp rate and power quantity at all times, a specific nominal power output is necessary. It is recommended to operate the power plant between 75 and 100% load due to the lower limits of the stack temperature in this power range.

Table 5-34: Results for system configuration CE3

System configuration	Electrical cover rate [%]	Partial load point minimum [% of full load]	Self-adjusting minimum temperature [°C]	Ramp-up rate at minimum temperature [% of max. power output per minute]
C3	100	33	760	52

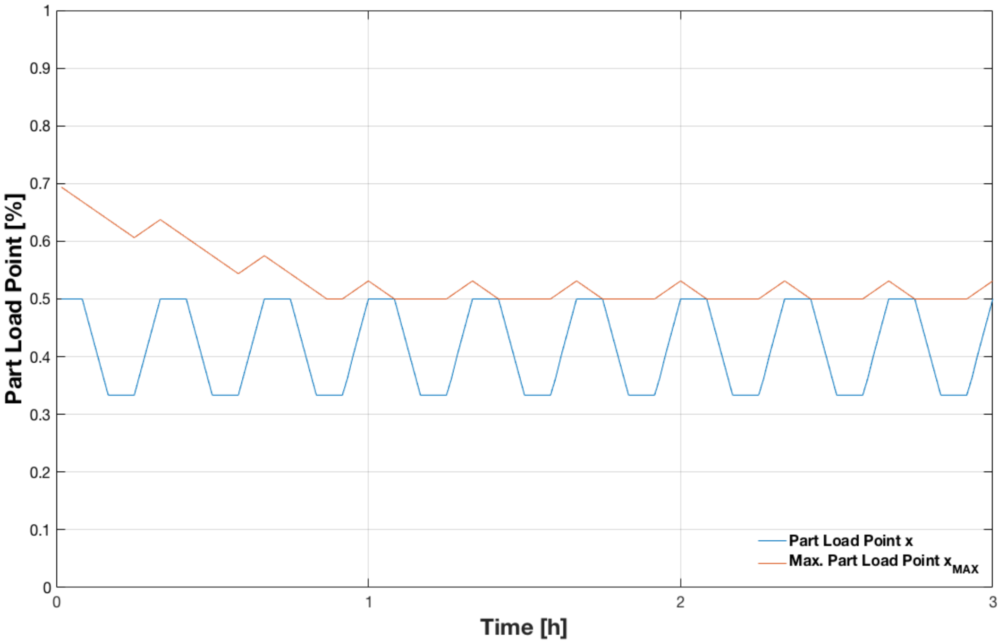


Figure 5-25: System configuration CE3 – Partial load point (Secondary)

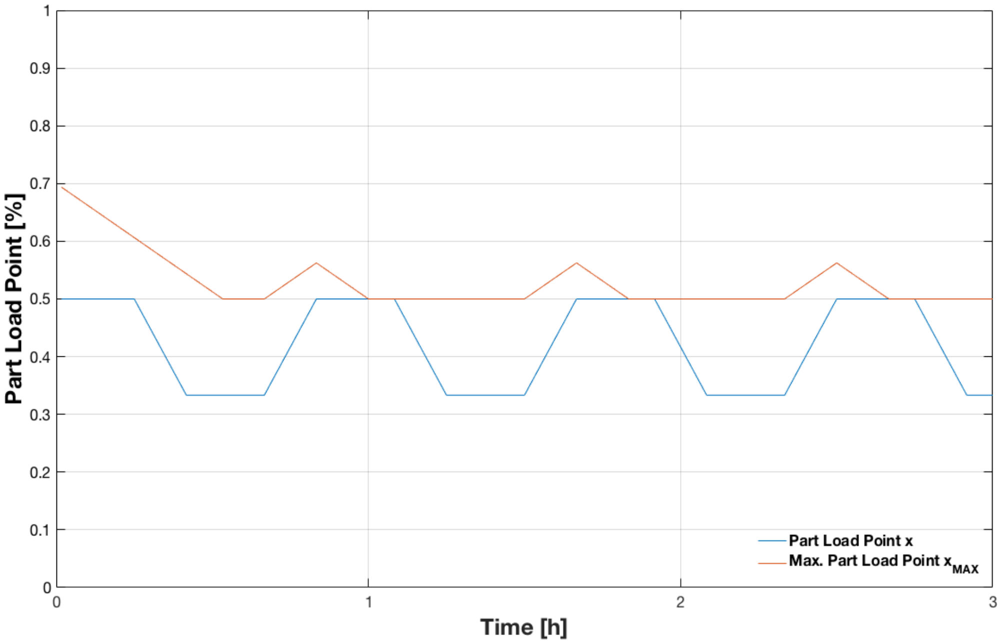


Figure 5-26: System configuration CE3 – Partial load point (Tertiary)

If operational mode CE2 should not be possible or even intended, it is also feasible to scale up the system and therefore increase the total power output. This ensures a high enough self-adjusting stack temperature at the minimal required power output. Nevertheless, this operational mode results in very little full load hours. An example for this operational mode CE3 for secondary as well as tertiary control energy is shown in *Figure 5-25* and *Figure 5-26*.

Table 5-35: Comparison of CE1, CE2 and CE3

System configuration	Electrical cover rate [%]	Partial load point minimum [% of full load]	Self-adjusting minimum temperature [°C]	Ramp-up rate at minimum temperature [% of max. power output per minute]
C1	< 100	50	780	75
C2	100	75	T_{max} = 830	100
C3	100	33	760	52

Starting at 75 % load the SOFC stack temperature will be below the maximal temperature (T_{max}) of 830 °C. Nevertheless, after several initial ramp-ups in power the system temperature will increase and remain at T_{max}. For this application it is recommended to operate the system only above 75 % load while remaining at the maximal stack temperature in order to provide high power ramp-up rates at all times. Without temperature constancy above 75 % load or while operating in a different partial load range requires the determination of the ramp-up rate at the self-adjusting minimal temperature at the minimal partial load point. Taking this in consideration the nominal electrical power output of the system as well as the operational mode must further be adapted to each specific application.

5.1.1 Influence of the stack temperature on the system behavior

Another simulation of the secondary load prequalification profile was conducted to point out the different influences of the temperature on the maximum ramp-up rate and the maximum possible part load point for general system configurations.

The following table shows the self-adjusting minimum temperatures at specific partial load points in contrast to the corresponding ramp-up rates and the maximum possible part load points. The self-adjusting temperature at 75 % can vary depending on preceding ramping procedures.

Table 5-36: Variation of system start points

Variation of system start points	Partial load point [% of full load]	Self-adjusting minimum temperature [°C]	Ramp-up rate at minimum temperature [% of max. power output per minute]	Maximum possible part load point at minimum temperature [%]
I	0	720 *	3	50
II	50	780	75	70
(III)	≥ 75	805	100	80
(IV)	≥ 75	830	100	100

* 720 °C = minimum temperature to draw power

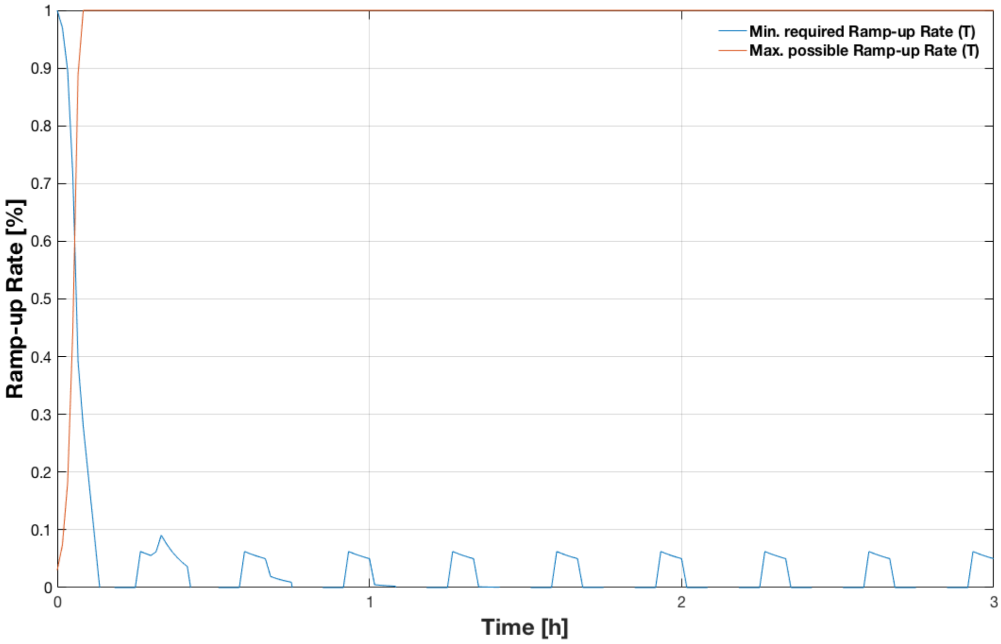


Figure 5-27: Variation I – Ramp-up rates

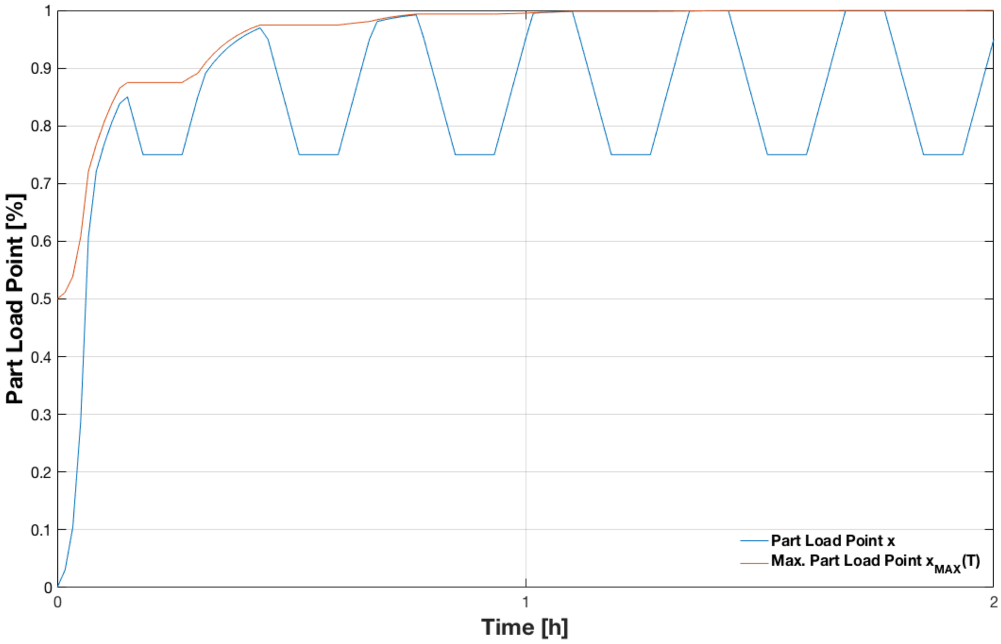


Figure 5-28: Variation I - Part load points

Variation I presents the minimal temperature of 720 °C for power ramping. *Figure 5-27* shows that the maximal ramp-up rate only has an influence in the very early stages of the power ramping process. *Figure 5-28* shows that the maximum part load point is to low over half the considered time range.

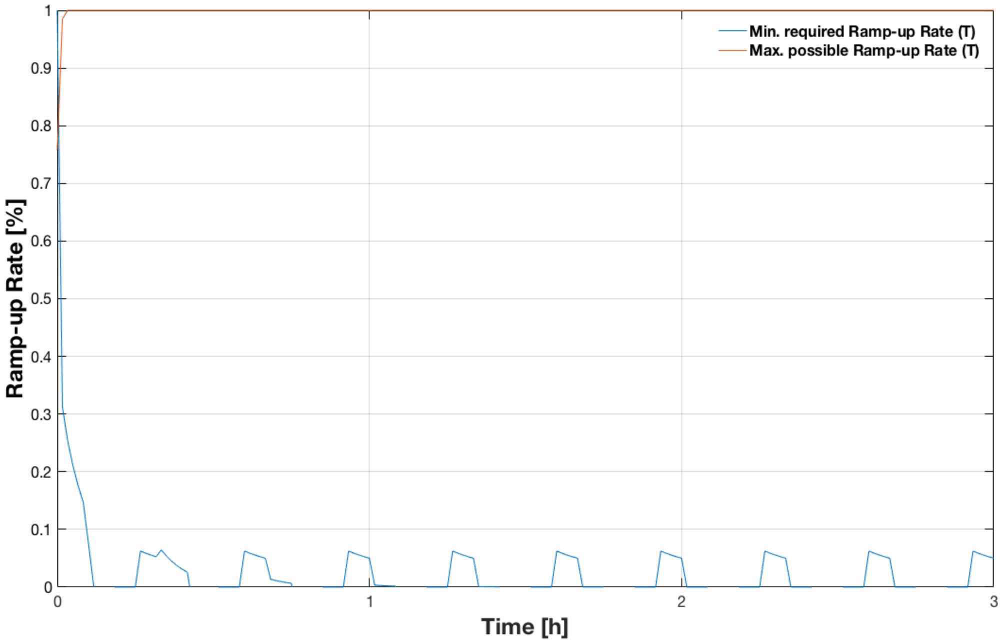


Figure 5-29: Variation II - Ramp-up rates

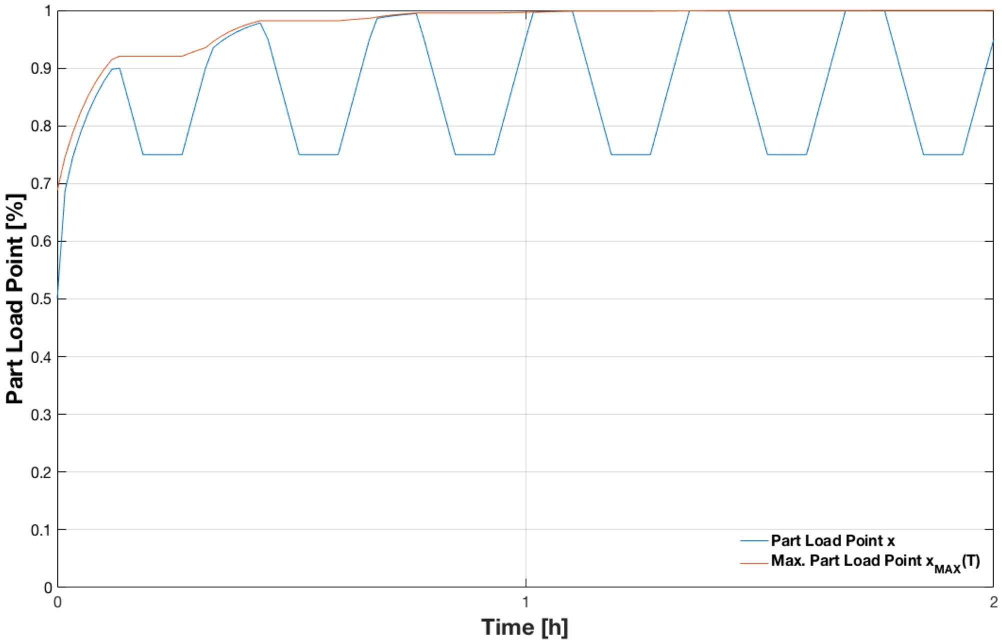


Figure 5-30: Varation II - Part load points

Variation II presents the temperature of 780 °C at 50 % load. *Figure 5-29* shows that the maximal ramp-up rate has no influence on the power ramping process. *Figure 5-30* shows that the maximal part load point is also too low over nearly half the considered time range.

As a result, the ramp-up is only a limiting factor at the very early stages of the starting process at low system temperatures as seen for Variation I.

5.2 Industrial load profile

In order of checking the suitability of SOFC systems for industrial power generation applications the power and heat demand profile of an industrial food company is simulated. For this application the average heat demand is a lot higher than the average electricity demand. In order to follow the load profile electricity controlled and heat controlled operation have been tested. The system configurations consist out of multiple sub-systems to determine the influences on operational parameters. Furthermore, the maximum power outputs of the SOFC systems are varied. The results are presented in the form of key parameters for industrial operation.

5.2.1 Electricity controlled

- Strategy A (Electricity controlled):
    - Aim: Full coverage of the thermal base load (constant minimal thermal load over the considered time range) in combination with optimal coverage of the electrical load profile
    - Operational mode: Electricity controlled
    - Method: Testing of multiple SOFC systems configurations

Table 5-37: System configuration A1 and A2

	System configuration A1		**System configuration A2**	
System	**A1-1**	**A1-2**	**A2-1**	**A2-2**
Nominal electrical power [kW]	5	5	5	5
Stack temperature [°C]	830	830	830	830
Operational mode [% load]	50 – 100	50 – 100	100	50 – 100

In contemplation of checking the combination of multiple SOFC systems configurations and operational modes for strategy A the system configurations A1 and A2 were simulated in the model. System configuration A1 consists out of two SOFCs that both operate thermally self-sustaining between 50 – 100 % load. For system configuration A2 only one SOFC operates between 50 – 100 % load while the other SOFC constantly operates at 100 % load.

Table 5-38: Results for system configuration A1

Parameter	Cover rate [%]	Demand [kWh/week]	Surplus energy produced [kWh/week]	Additional energy necessary [kWh/week]
Electrical	97	865	195	26
Thermal	6	8046	0	7563
Thermal-Base-Load	73	697	11	188

Figure 5-31 and *Figure 5-32* present the electrical load profile (blue) and the electrical output of the SOFC system (orange) over a time range of 4 weeks.

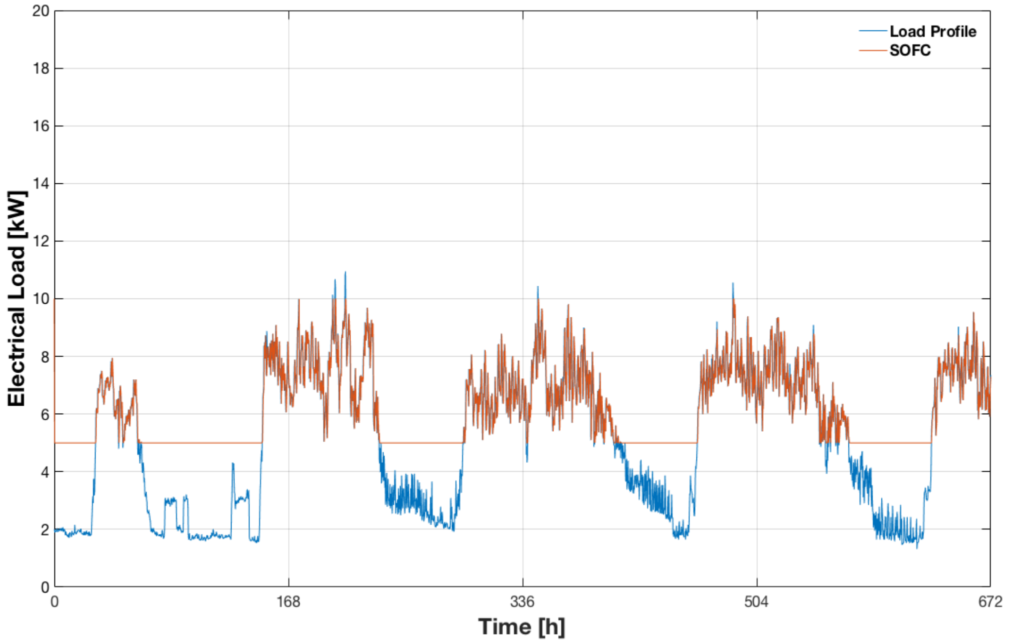


Figure 5-31: System configuration A1 – Electrical load

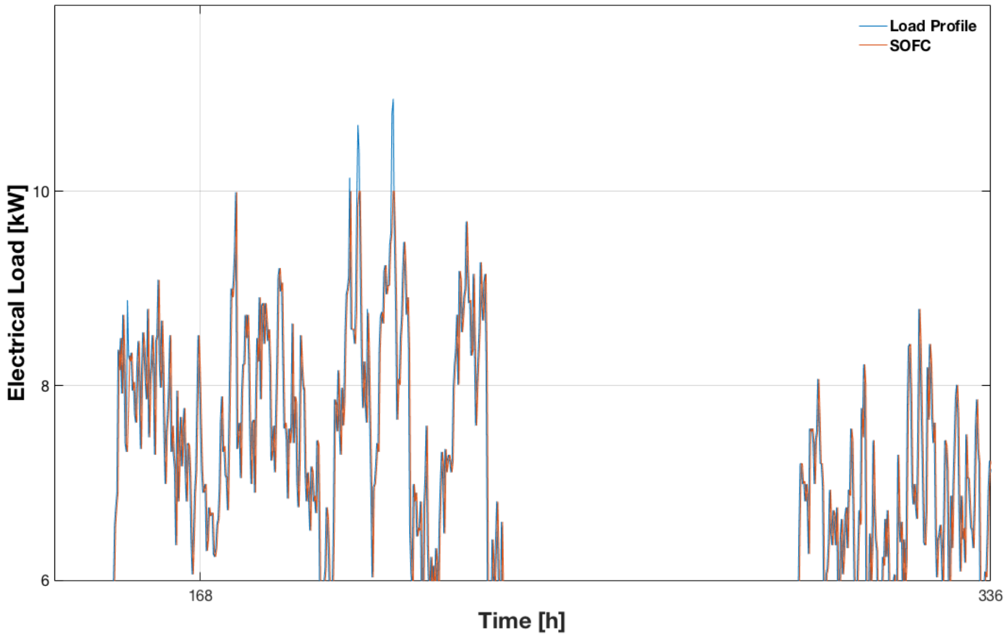


Figure 5-32: System configuration A1 – Electrical load (Zoom)

Figure 5-33 presents the thermal load profile (blue) and the thermal output of the SOFC system (orange) over a time range of 4 weeks.

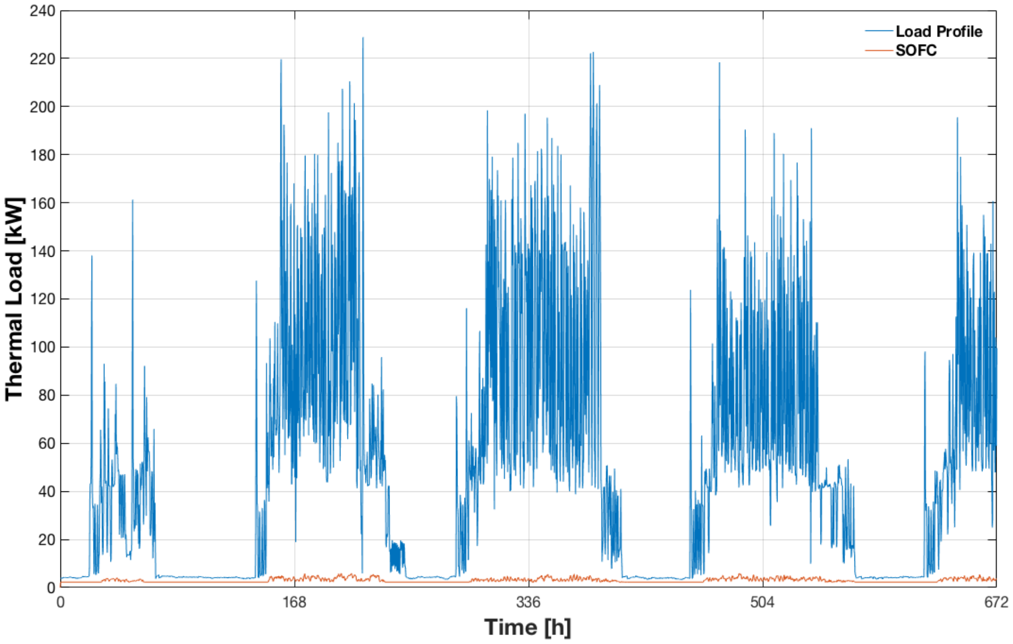


Figure 5-33: System configuration A1 – Thermal load

Figure 5-34 and *Figure 5-35* present the monthly load duration curve with the electrical power demand (blue) and the electrical output of the SOFC system (orange).

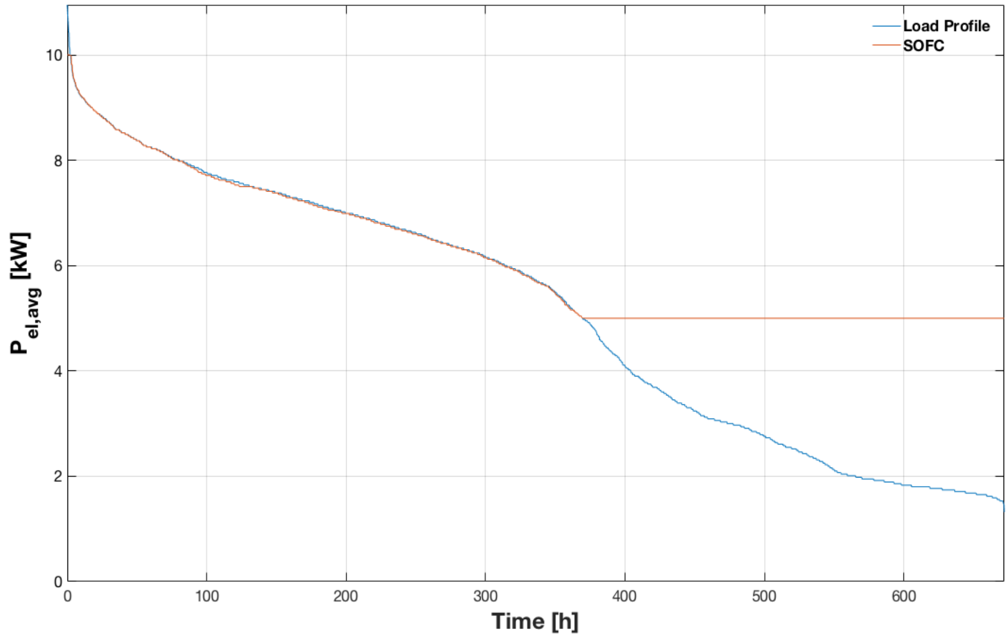


Figure 5-34: System configuration A1 – Electrical monthly load duration curve

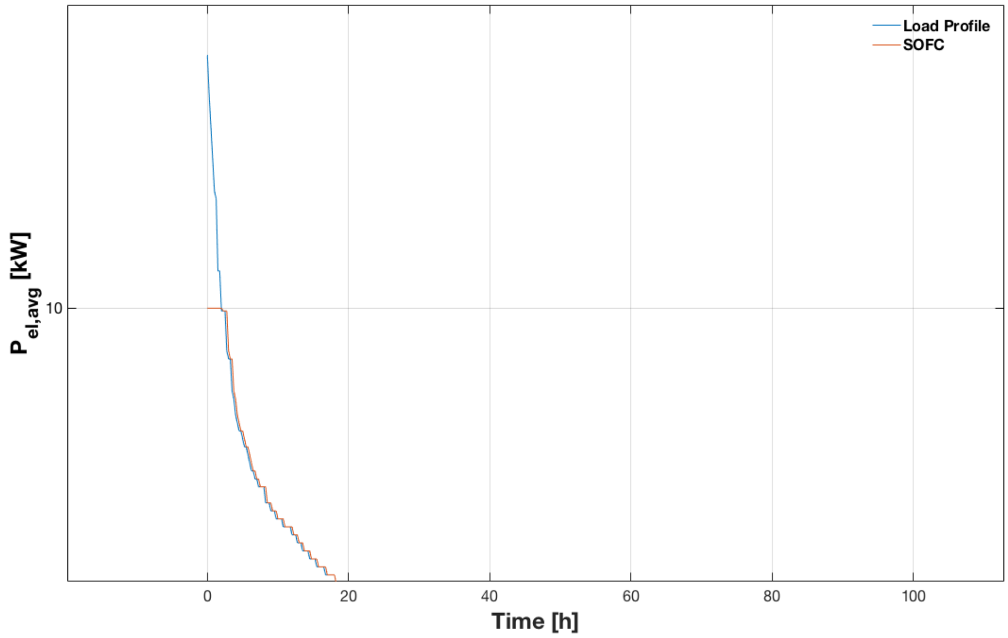


Figure 5-35: System configuration A1 – Electrical monthly load duration curve (Zoom)

Figure 5-36 presents the monthly load duration curve with the thermal power demand (blue) and the thermal output of the SOFC system (orange).

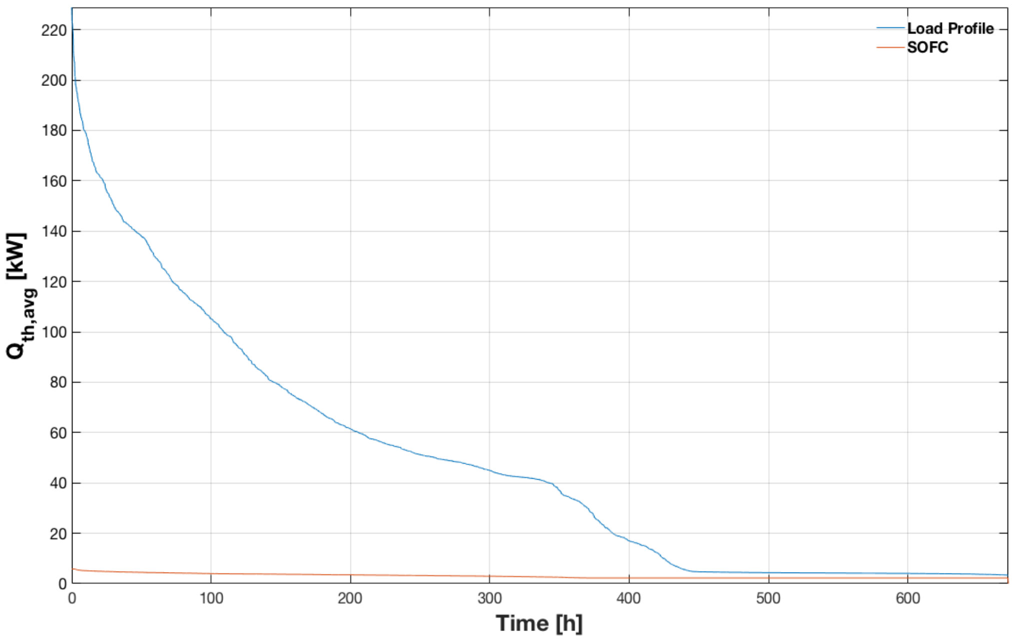


Figure 5-36: System configuration A1 – Thermal monthly load duration curve

The lower minimum of 50 % load for the systems A1-1 and A1-2 sets the minimal combined power output to 5 kW, while the maximal combined power output is 10 kW. In between the range of 50 – 100 % load the system configuration A1 tries to adapt the load profile. The thermal power demand is much higher than the electrical power demand in this application. The thermal output of the system configuration A is too small to cover even the thermal base-load as seen in *Figure 5-33*. The overproduction of electrical power is presented by the gap between the power demand line (blue) and the electrical output of the SOFC system (orange) over a time range of 4 weeks in *Figure 5-34.* The underproduction of thermal power is presented by the gap between the power demand line (blue) and the output of the SOFC system (orange) over a time range of 4 weeks in *Figure 5-36.*

While the electrical power demand is covered almost completely, a large amount of surplus electrical energy for feed-in to the grid or local energy storage is produced. In order to cover the full electrical power demand a battery storage must be able to provide 0,9 kW electrical power at all times. In order to cover the whole thermal power demand a large amount of thermal energy is necessary. This energy can either be provided by an additionally added gas fired heating system or by external sources. Furthermore, both systems A1-1 and A1-2 operate mostly at 50 % part load, which is not very economical.

Table 5-39: Results for system configuration A2

Parameter	Cover rate [%]	Demand [kWh/week]	Surplus energy produced [kWh/week]	Additional energy necessary [kWh/week]
Electrical	99	865	431	9
Thermal	9	8046	0	7322
Thermal-Base-Load	99	697	4	7

Figure 5-37 presents the electrical load profile (blue) and the electrical output of the SOFC system (orange) for system configuration A2.

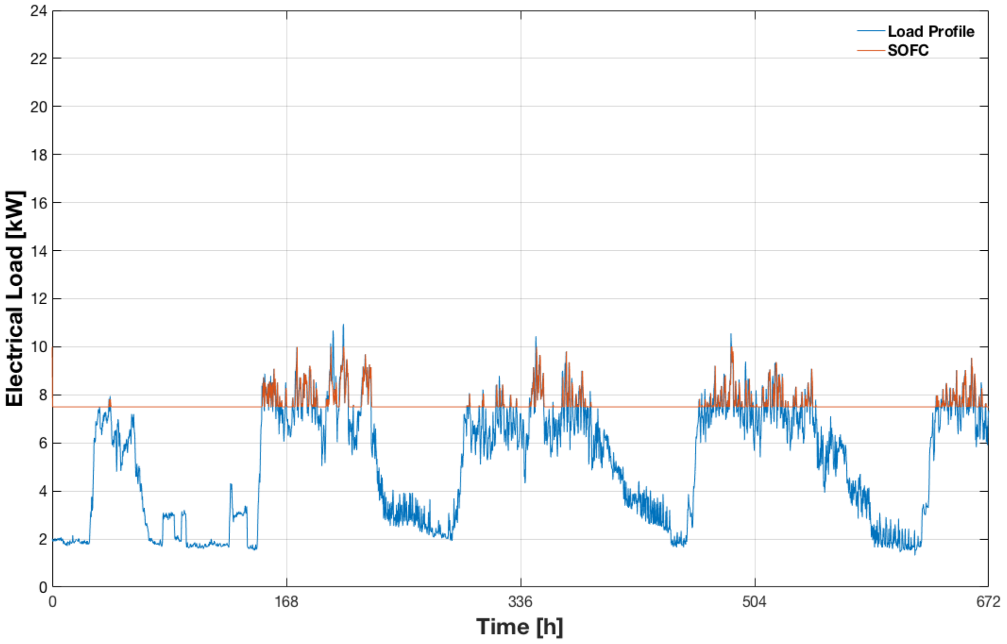


Figure 5-37: System configuration A2 – Electrical load

Figure 5-38 presents the thermal load profile (blue) and the thermal output of the SOFC system (orange) of system configuration A2

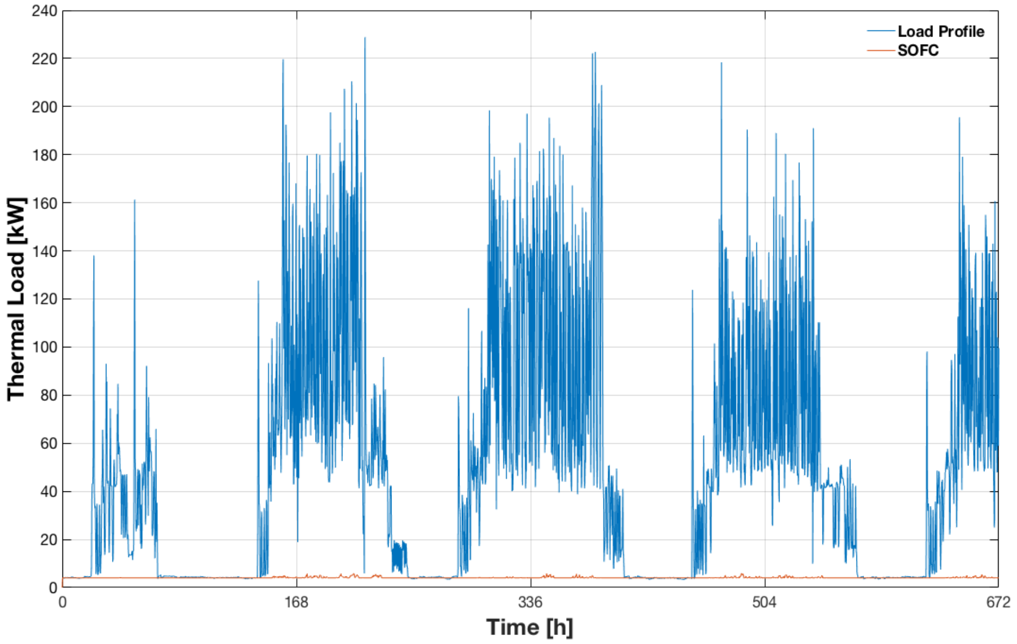


Figure 5-38: System configuration A2 – Thermal load

Figure 5-39 and *Figure 5-40* present the monthly duration curve with the electrical power demand (blue) and the electrical output of the SOFC system (orange).

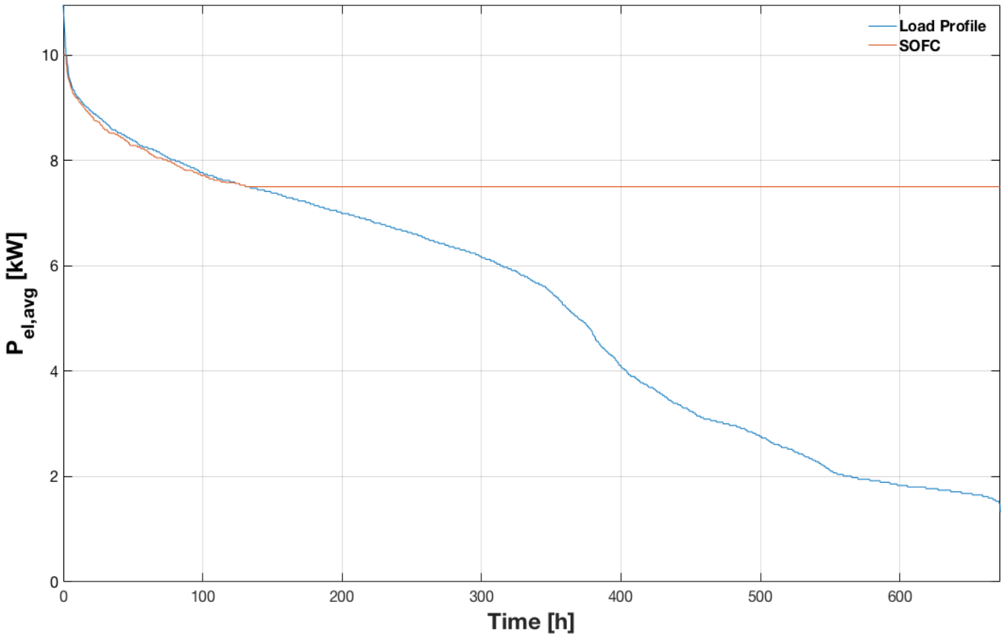


Figure 5-39: System configuration A2 – Electrical monthly load duration curve

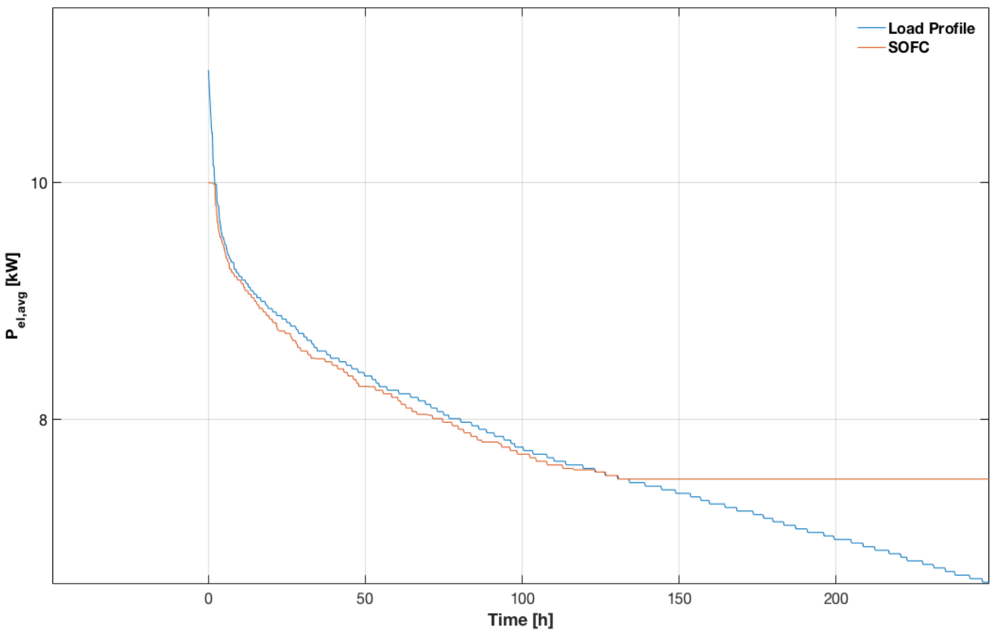


Figure 5-40: System configuration A2 – Electrical monthly load duration curve (Zoom)

Figure 5-41 presents the monthly load duration curve with the thermal power demand (blue) and the thermal output of the SOFC system (orange).

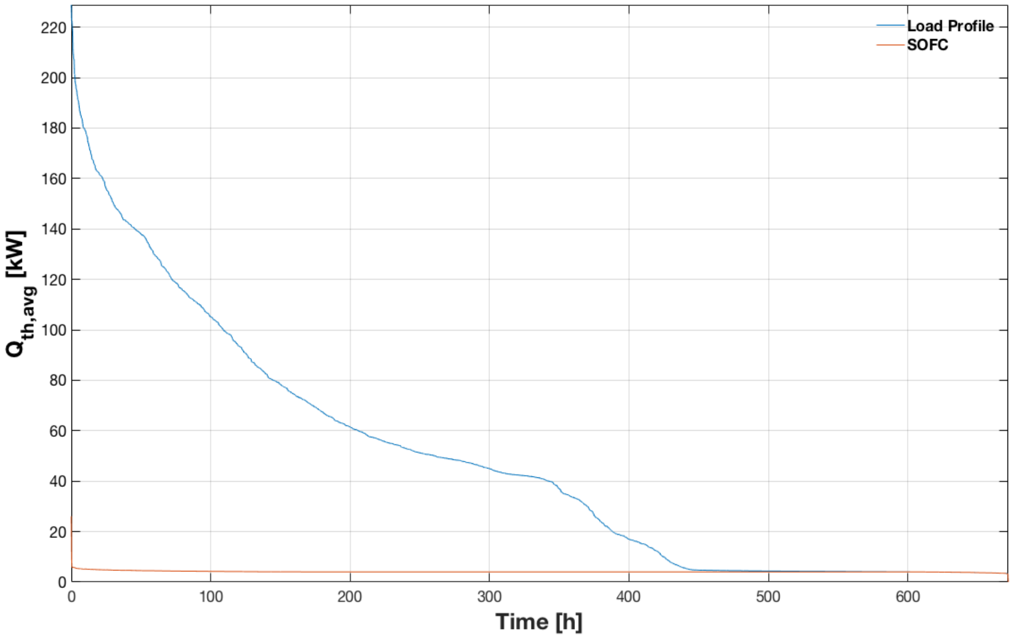


Figure 5-41: System configuration A2 – Thermal monthly load duration curve

System A2-1 operates at 100 % load at all times, while system A2-2 still is in load following. The lower combined power minimum is 7,5 kW, while the maximum remains 10 kW. The thermal power output of the SOFC system is able to cover the thermal base-load completely. The little variations in *Figure 4-40* are a result of the dependency of the maximum possible part load point on the stack temperature as discussed in the previous chapter.

The electrical power demand and thermal base load demands are covered completely. Still a larger amount of surplus electrical energy for feed-in to the grid or local energy storage is produced. In order to cover the whole thermal power demand still a large amount of thermal energy is necessary. This energy can either be provided by an additionally added gas fired heating system or by external sources. While system A2-1 operates at full load at all times, system A2-2 operates about 80 % of the time at 50 % part load. As a result, the SOFC system is able to produce enough heat to cover the thermal base load in the industrial application while also covering the electrical load.

Table 5-40: Comparison of A1 and A2

Parameter	**System config.**	**Cover rate [%]**	**Demand [kWh/week]**	**Surplus energy produced [kWh/week]**	**Additional energy necessary [kWh/week]**
Electrical	A1	97	865	195	26
	A2	99	865	431	9
Thermal	A1	6	8046	0	7563
	A2	9	8046	0	7322
Thermal-Base-Load	A1	73	697	11	188
	A2	99	697	4	7

While the electrical cover rates are mostly even for system configuration A1 and A2 only system configuration A2 is able to cover the full thermal base load. The overproduction of electrical power is higher for system configuration A2 when compared to A1 as a result of one system operating constantly at 100 % load. The underproduction of thermal power is a little smaller for system configuration A2 when compared to A1.

5.2.2 Heat controlled

For this industrial application the average heat demand is a lot higher than the electricity demand. In contemplation of checking the suitability of the SOFC for heat controlled strategy B the system configurations B1 was simulated in the model.

- Strategy B (Heat controlled):
    - Aim: Full coverage of the thermal load in combination with optimal coverage of the electrical load profile
    - Operational mode: Heat controlled
    - Method: Testing of multiple SOFC systems configurations

Table 5-41: System configuration B1

	System configuration B1	
System	**B1-1**	**B1-2**
Nominal electrical power [kW]	5	5
Stack temperature [°C]	830	830
Operational mode [% load]	50 – 100	50 – 100

System configuration B1 is similar to system configuration A1 except for the heat controlled operational mode.

Table 5-42: Results for system configuration B1

Parameter	**Cover rate [%]**	**Demand [kWh/week]**	**Surplus energy produced [kWh/week]**	**Additional energy necessary [kWh/week]**
Electrical	100	865	698	0
Thermal	11	8046	0	7160
Thermal-Base-Load	100	697	20	0

Figure 5-42 presents the thermal load profile (blue) and the thermal output of the SOFC system (orange) of system configuration B1.

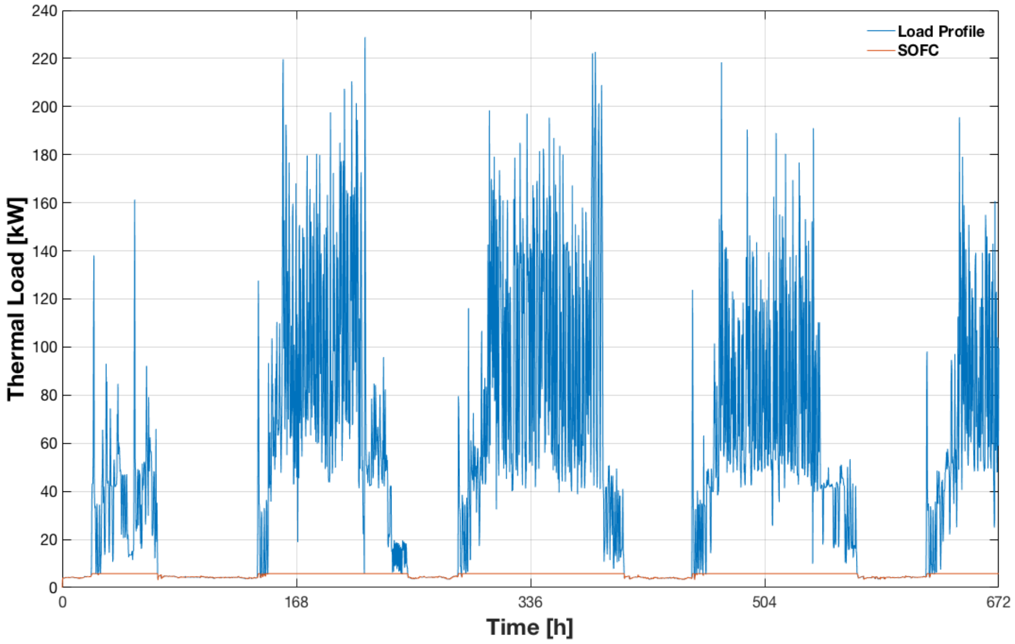


Figure 5-42: System configuration B1 – Thermal load

Figure 5-43 presents the electrical load profile (blue) and the electrical output of the SOFC system (orange) for system configuration B1.

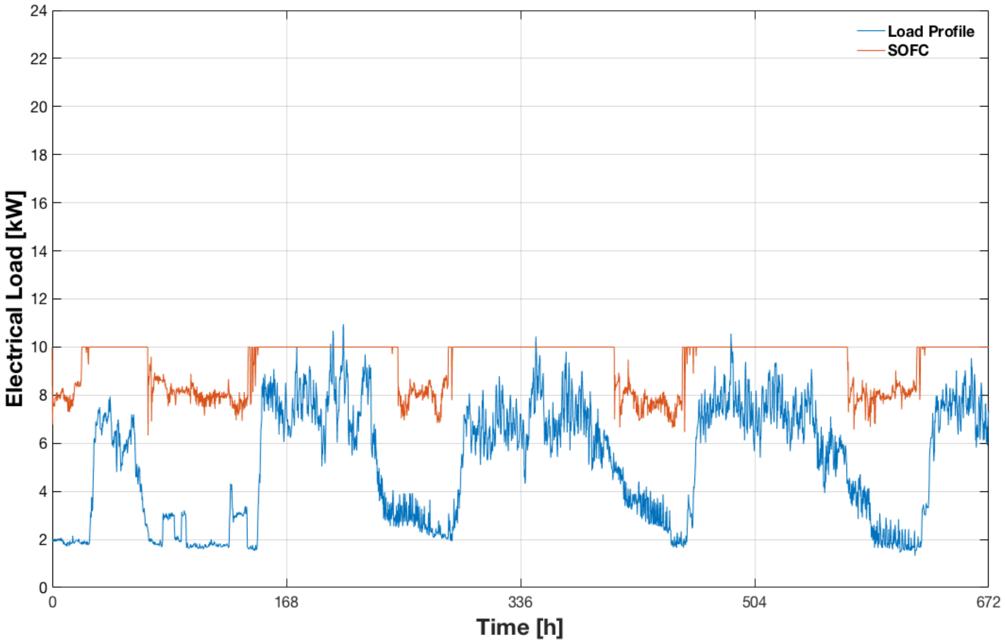


Figure 5-43: System configuration B1 – Electrical load

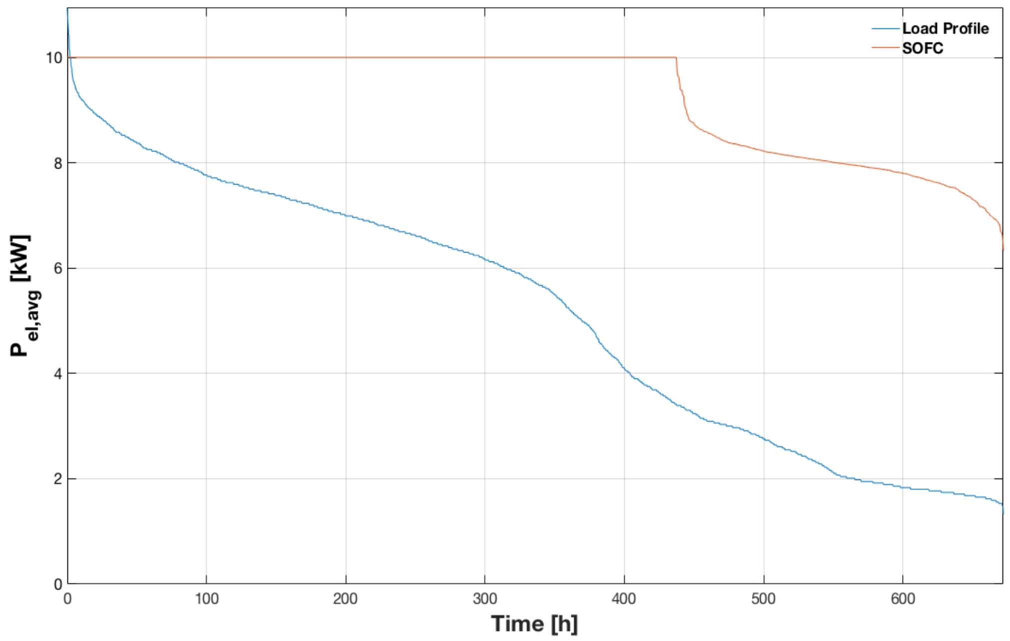


Figure 5-44: System configuration B1 – Electrical monthly load duration curve

The thermal power output of the SOFC system is able to cover the thermal base-load. The electrical output of the SOFC system is completely apart from the load profile and a large amount of surplus energy is produced as shown in *Figure 4-44*. In order to cover the full thermal load profile, a system with a much higher output has to be implemented. This will lead to an enormous amount of surplus electrical energy for similar applications, with a much higher heat than electricity demand and to very non-economical operational modes.

Table 5-43: Comparison of A1, A2 and B1

Parameter	System config.	Cover rate [%]	Demand [kWh/week]	Surplus energy produced [kWh/week]	Additional energy necessary [kWh/week]
Electrical	A1	97	865	195	26
	A2	99	865	431	9
	B1	100	865	698	0
Thermal	A1	6	8046	0	7563
	A2	9	8046	0	7322
	B1	11	8046	0	7160
Thermal-Base-Load	A1	73	697	11	188
	A2	99	697	4	7
	B1	100	697	20	0

The electrical power demand and thermal base load demands are covered completely. Still a much larger amount of surplus electrical energy compared to system configuration A is produced. Nevertheless, the coverage of the full thermal load profile is only a little higher than for system configuration A. This is due to the relatively small maximal power output of the system configuration. An advantage to system configuration A could be that the systems B1-1 and B1-2 operate at full load at 100 % and 66 % of the time. Although both systems can follow the load demand, only one needs to adjust the output for this application while the other remains at full load at all times.

5.2.3 Variation of the maximum power output

In order of checking the differences of a varying maximum power output of the SOFC system for this industrial power distribution application, the following strategy C has been applied.

- Strategy C:
  - Aim: Full coverage of the electrical load in combination with optimal coverage of the thermal load profile
  - Operational mode: Electricity controlled
  - Method: Testing of multiple SOFC systems configurations

Table 5-44: System configuration C1 and C2

	System configuration C1	System configuration C2
Nominal electrical power [kW]	2,6	11
Stack temperature [°C]	830	830
Operational mode [% load]	50 – 100	50 – 100

The nominal electrical outputs of the system configurations are designed at the minimum electrical power demand (C1) and the maximum electrical power demand (C2) of the load profile. The operational mode is in the thermally self-sustaining power range from 50 – 100 % load.

Table 5-45: Results for system configuration C1

Parameter	Cover rate [%]	Demand [kWh/week]	Surplus energy produced [kWh/week]	Additional energy necessary [kWh/week]
Electrical	47	865	3	458
Thermal	3	8046	0	7805
Thermal-Base-Load	33	697	0	467

Table 5-46: Results for system configuration C2

Parameter	Cover rate [%]	Demand [kWh/week]	Surplus energy produced [kWh/week]	Additional energy necessary [kWh/week]
Electrical	97	865	232	26
Thermal	6	8046	0	7563
Thermal-Base-Load	75	697	8	174

The following figures presents the monthly load duration curves with the electrical power demand (blue) and the electrical output of the SOFC system (orange) for the system configuration C1 and C2.

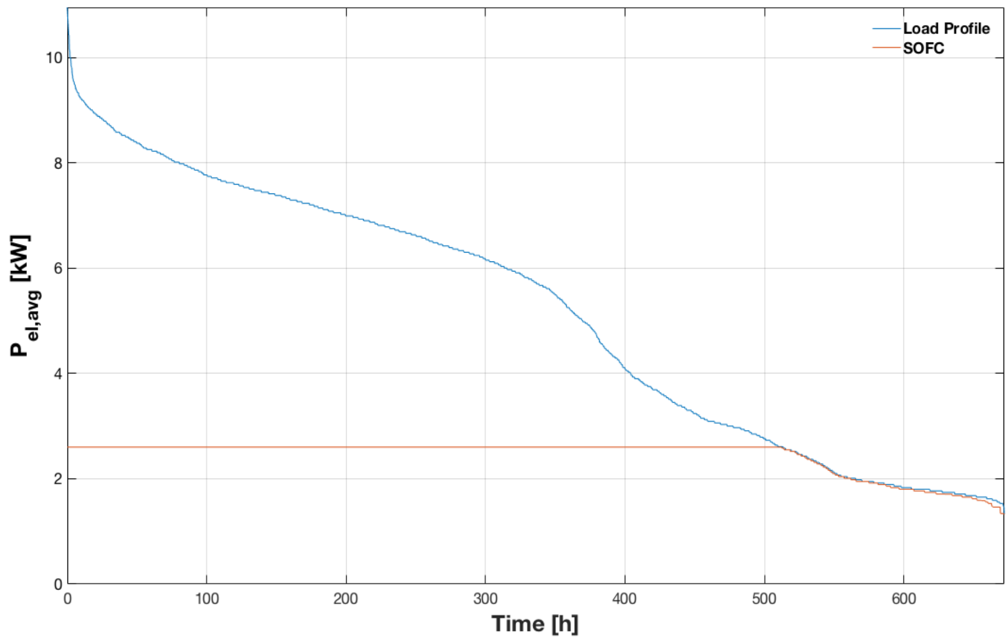


Figure 5-45: System configuration C1 – Electrical monthly load duration curve

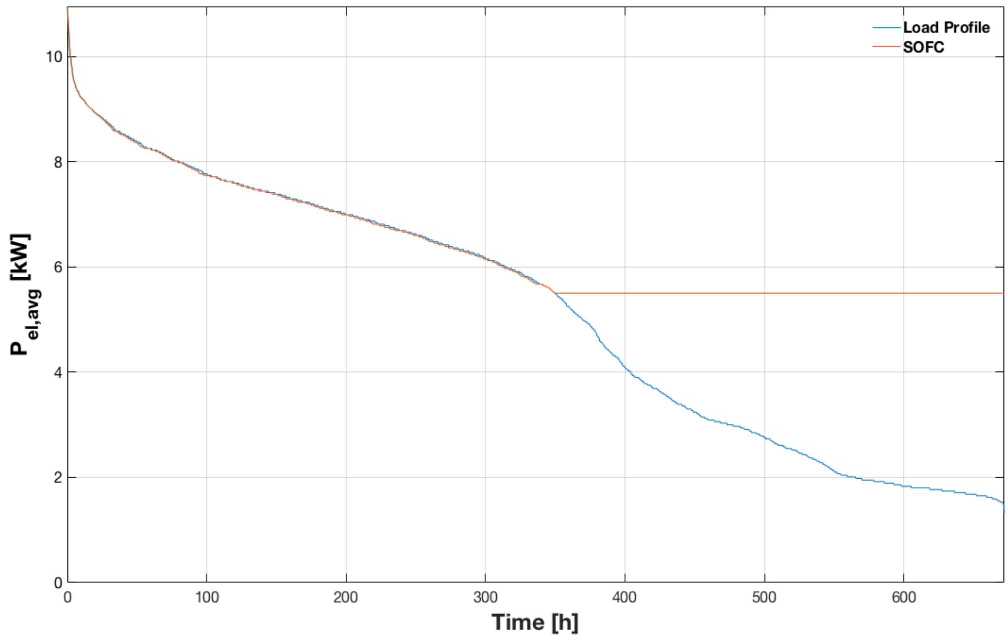


Figure 5-46: System configuration C2 – Electrical monthly load duration curve

While for C1 an underproduction of electrical power is presented, the monthly load duration curves of C2 shows an overproduction of energy over the considered time range.

Choosing the right system for a specific application mainly depends on the priorities of the system operator.

- Designing SOFC systems on the basis of the maximum electrical power demand of the application results in high cover rates, but a large amount of surplus energy and the system operating at 58 % of the time at 50 % load.
- Designing SOFC systems on the basis of the minimum electrical power demand of the application results in low cover rates and a large amount of residual energy needed, but the system operating at 78 % of the time at full load.

The optimal system configuration for the industrial application can be designed by combination of different parameters depending on the specific priorities. The cover rates are relatively even for both electricity and heat controlled operational mode. Nevertheless, during electricity controlled operation less surplus energy is produced and there are less full load operating hours than compared to heat controlled operation. Furthermore, the combination of two dynamic load following SOFC systems present lower cover ratios of the thermal base load, only little full load operating hours and the production of a large amount of surplus energy compared to the combination of a dynamic and a static non load following system. Designing the power supply unit in order to cover the maximal required power of this industrial application leads to high electrical cover rations, a high amount of surplus energy and only little full load operating hour.

Table 5-47: Design parameters: Industrial application

Parameter	Electrical cover ratio	Cover ratio of thermal base load	Full load operating hours	Surplus energy
Electricity controlled	high	high	less	low
Heat controlled	high	high	more	high
Dynamic systems	-	lower	less	higher
Dynamic + static system	-	higher	more	lower
Power output at min. demand	low	-	more	low
Power output at max. demand	high	-	less	high

5.3 Industrial load profile in combination with supply of control energy

The following simulation checks the suitability of SOFC systems for industrial applications in combination with additional distribution of secondary control energy. Therefore, the power and heat demand profile of a typical industrial company and a typical secondary control energy load profile have been combined.

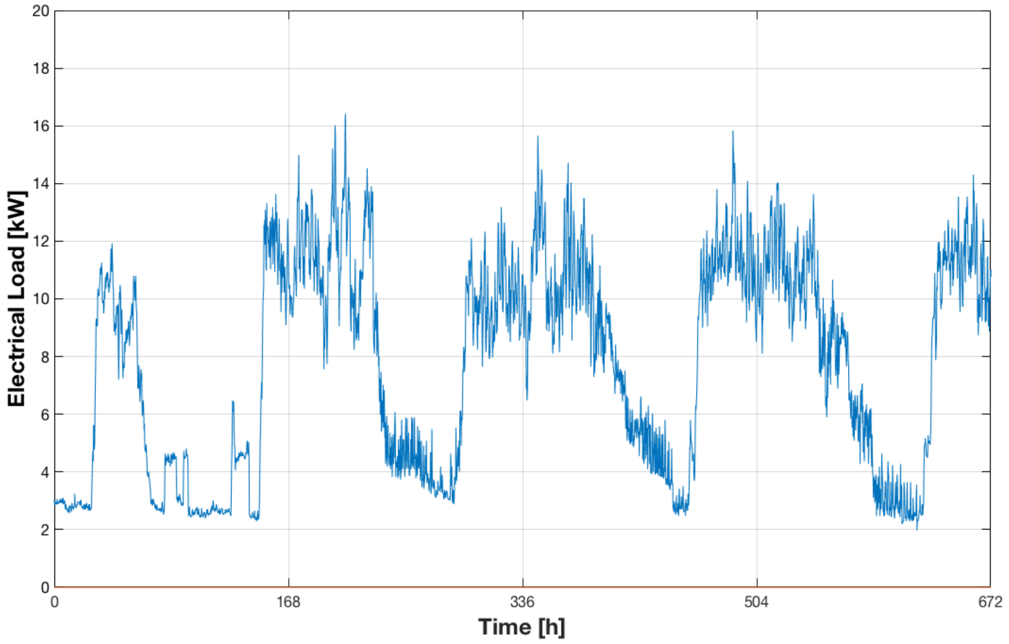


Figure 5-47: Industrial load profile for system configuration D1

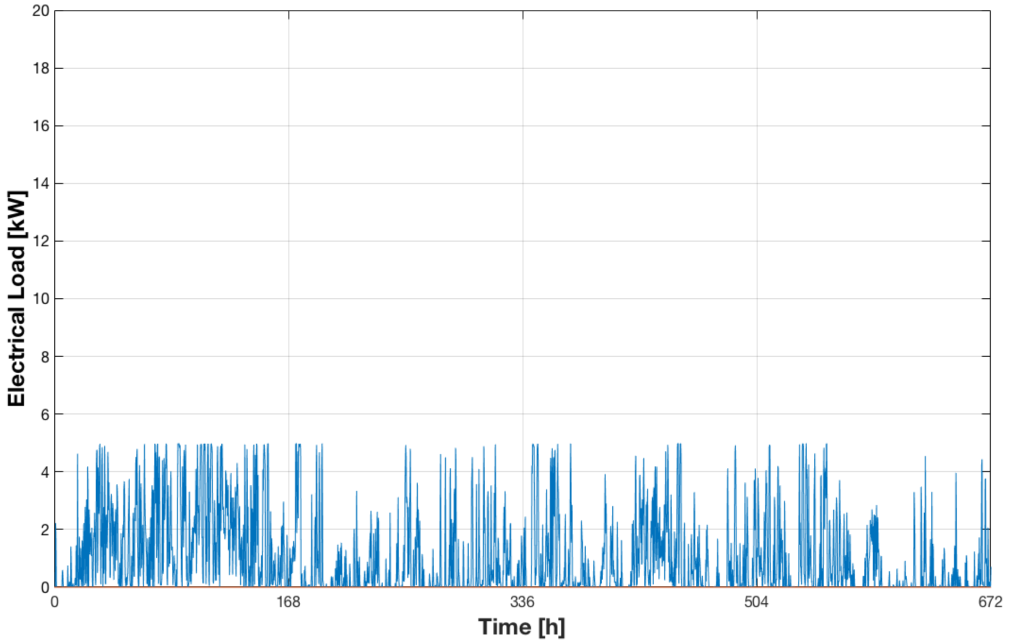


Figure 5-48: Control energy profile for system configurations D1-2 and D2-2

The industrial load profile is scaled to a maximum power output of 15 kW (Figure 5-46) for system configuration D1 and to 45 kW for configuration D2.

The following strategy has been applied for this simulation:

- Strategy D:
    - Aim: Coverage of the electrical industrial load profile with additional distribution of secondary control energy
    - Operational mode: Electricity controlled
    - Method: Testing of multiple SOFC systems configurations

Table 5-48: System configuration D1 and D2

	System configuration D1		**System configuration D2**	
System	**D1-1**	**D1-2**	**D2-1**	**D2-2**
inkl. supply of control energy	no	yes	no	yes
Nominal electrical power for industrial load [kW]	15	15	45	45
Nominal electrical power for control energy [kW]	0	5	0	5
Stack temperature [°C]	830	830	830	830
Operational mode A [% load]	10 – 100	-	10 – 100	-
Operational mode B [% load]	50 – 100	-	50 – 100	-
Operational mode C [% load]	-	75 – 100 %	-	75 – 100 %

The system configurations D1-1 and D2-1 only try to adapt to the industrial load profile while system configuration D1-2 and D2-2 additionally supply 25 % and 10 % of their nominal electrical power output as control energy.

The maximal required ramp-up rate of 5 kW/min for this application requires a minimal stack temperature of 760 °C which is the self-adjusting temperature at 37,5 % load. However, if the industrial load is at maximal capacity, the maximal part load point the system must be able to ramp-up to is 100 % load. As a result, the limiting factor for combination of the industrial load profile and the supply of control energy is that the system must operate between 75 – 100 % load (Operational mode C) at maximal system temperature. This is necessary to provide the maximal possible required system output continuously.

Table 5-49: Results for system configuration D1

Parameter	System D1-1-A / D1-1-B		System D1-2
Electrical output [kW]	15		15 + 5
Operational mode [% load]	10 – 100	50 – 100	75 – 100
Electrical cover rate [%]	100	100	100
Thermal base load cover rate [%]	37	27	47
Surplus electrical energy [kWh/week]	1	262	1.053

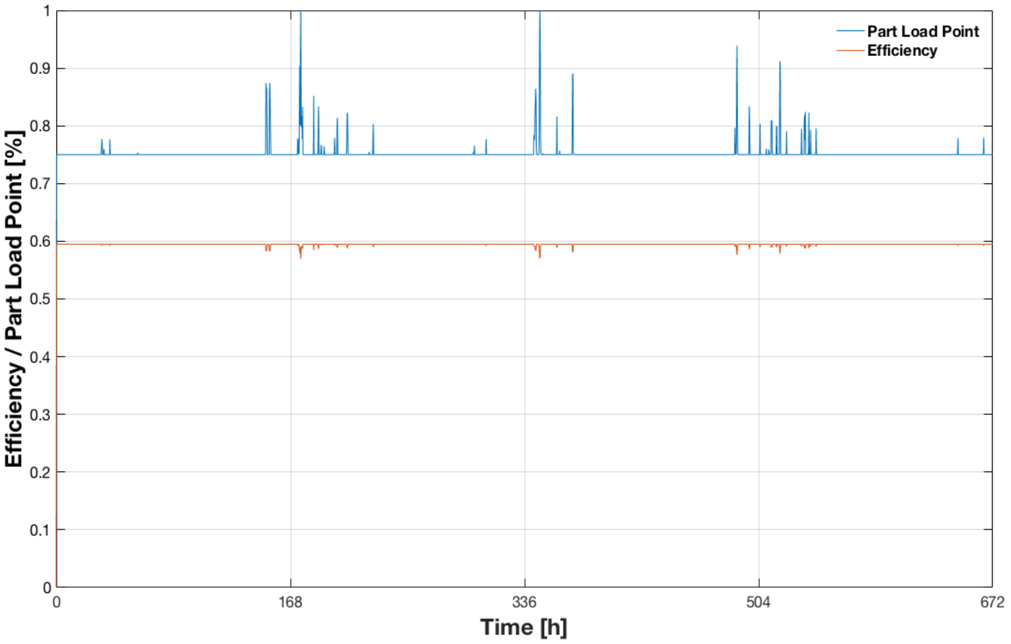


Figure 5-49: System configuration D1-2 – Efficiency / Part load point

While the electrical power demand is covered completely for all system configurations D1, the coverage of the thermal load profile varies. Additionally, a larger amount of surplus electrical energy is produced when combining the industrial load profile and the supply of control energy (D1-2), if compared to the industrial load profile alone (D1-1). This is a result of the different operational modes, especially the minimum required range from 75 – 100 % of system D1-2.

Table 5-50: Results for system configuration D2

Parameter	System D2-1-A / D2-1-B		System D2-2
Electrical output [kW]	45		45 + 5
Operational mode [% load]	10 – 100	50 – 100	75 – 100
Electrical cover rate [%]	100	100	100
Thermal base load cover rate [%]	100	82	100
Surplus electrical energy [kWh/week]	2	787	2.290

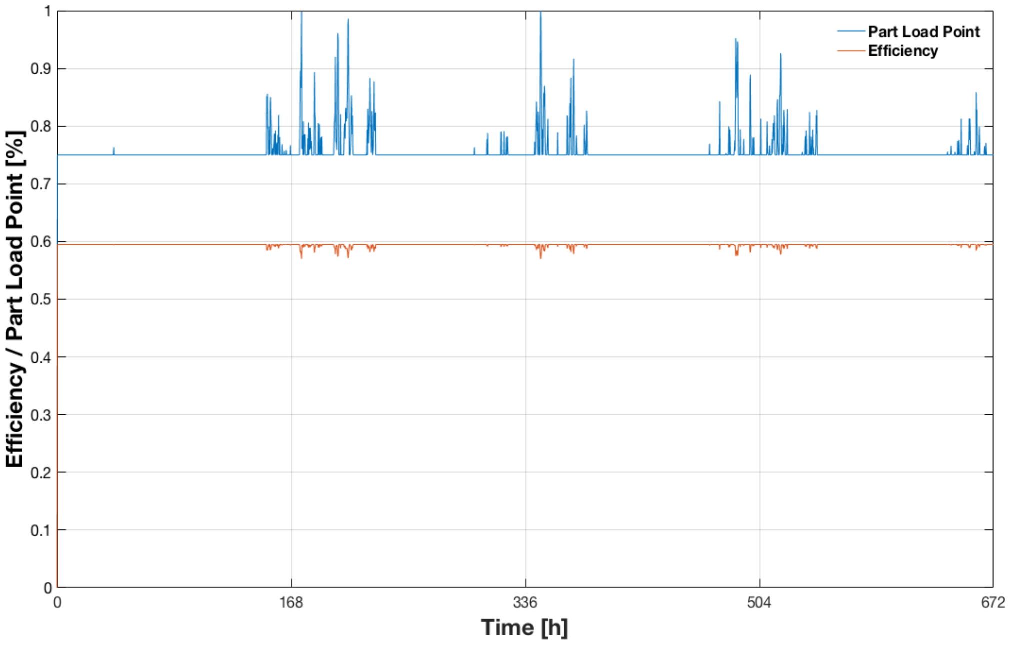


Figure 5-50: System configuration D2-2 – Efficiency / Part load point

The electrical power demand is covered completely for all system configurations D2 as well the coverage of the thermal load profile is up to 100 %. Again, a larger amount of surplus electrical energy is produced for the combination of the industrial load profile and the supply of control energy (D2-2), compared to the industrial load profile alone (D2-1).

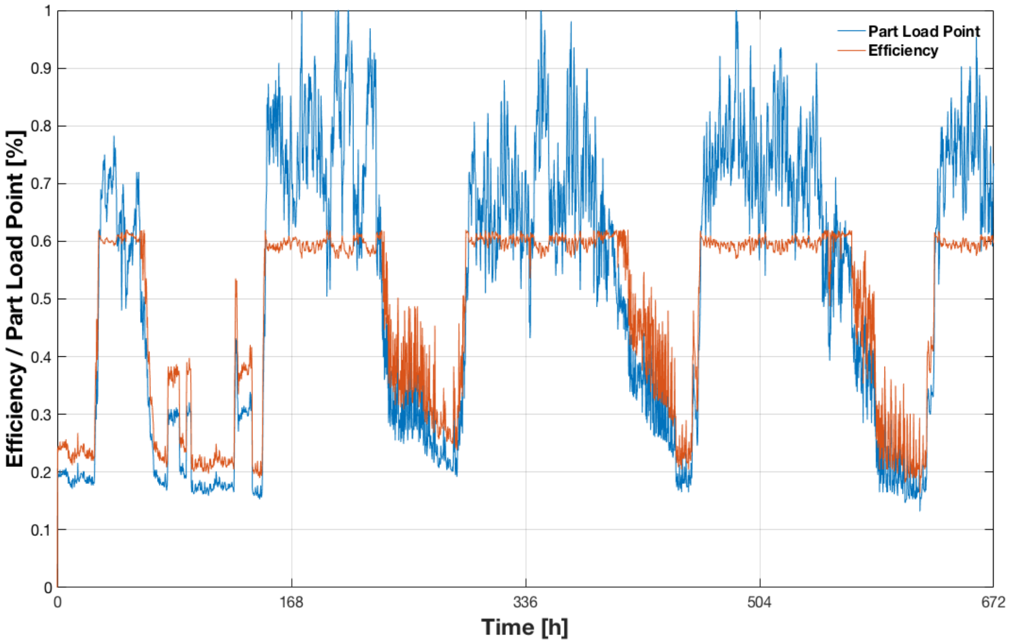


Figure 5-51: System configuration D1-1 and D2-1 – Efficiency / Part load point

The demand of control energy is very sporadic and leads to very little operational hours above 75 % load for the combined application, as seen in *Figure 5-49* and *5-50*. The surplus produced electrical energy must be used properly in order to remain economical. Systems with a smaller nominal electrical power output are affected stronger. The combined application benefits from no heavy losses in electrical efficiency because of the operational mode from 75 – 100 % load. This is the opposite for the industrial application alone (*Figure 5-51*). As a result, SOFC systems are mainly limited to the dependency of the maximum power output the system can ramp-up to specific temperatures. The system must remain at maximum temperature in order to pass the prequalification requirements as discussed before. Choosing a different operational window as discussed in *Chapter 5.1*, is also not an economical solution. Nevertheless, if this application is considered the systems nominal electrical output should be very high compared to the supplied control energy.

5.4 Residential load profile

The following simulation checks suitability of SOFC systems for a residential application. Therefore, the power and heat demand profile of typical summer and winter month of a residential complex has been simulated. The thermal load profile includes heat demand for space heating and domestic hot water. Two different SOFC system configurations have been tested. Additionally, a gas fired heating system can be added if required for additional heat supply in the winter months, in order to cover the full thermal load profile.

The following strategy has been applied:

- Strategy E:
  - Aim: Full coverage of the electrical load profile in combination with optimal coverage of the thermal load profile
  - Operational mode: Electricity controlled
  - Method: Testing of different system outputs, operational modes and power to heat ratios

Table 5-51: System configurations E1 and E2

	System configuration E1	**System configuration E2**
Nominal electrical power [kW]	5	10
Stack temperature [°C]	830	830
Operational mode A [% load]	10 – 100	10 – 100
Operational mode B [% load]	50 – 100	50 – 100
Operational mode C [% load]	75 – 100	75 – 100
Operational mode D [% load]	100	100

Every partial load point represents a specific power to heat ratio, which is presented in the following table.

Table 5-52: Power to heat ratios

Partial load point [%]	**Power to heat ratio [-]**
10	0,16
25	0,53
50	2,20
75	1,95
100	1,73

The thermal coverage in the following examples is calculated, with the usage of an infinite thermal energy storage unit which stores all produced surplus energy, while only distributing the requested amount by the thermal load profile. In summer all the different operational modes present very good cover rates for the electrical as well as the thermal load profile. Depending on how the additionally produced electrical and thermal energy can be utilized, the operational mode has to be chosen for different periods. For example, if a reasonable price for electrical energy feed-in to the grid is available the system should operate at 100 % load. This also benefits the overall economics of the system as a result of more full load hours. Otherwise the system should operate in the load following mode in order to keep surplus energy production low.

Table 5-53: Results for system configuration E1 (Summer)

Parameter	System E1-A	System E1-B	System E1-C	System E1-D
Electrical output [kW]	5	5	5	5
Operational mode [% load]	10 – 100	50 – 100	75 – 100	100
Power to heat ratio [-]	0,40 – 2,20	1,75 – 2,20	1,75 – 1,90	1,75
Electrical cover rate [%]	99	98	99	99
Thermal cover rate [%]	100	100	100	100
Electrical power demand [kWh/week]	104	104	104	104
Thermal power demand [kWh/week]	52	52	52	52
Surplus electrical energy [kWh/week]	1	65	233	428
Surplus thermal energy [kWh/week]	9	15	120	270
Residual electrical energy [kWh/week]	1	2	1	1
Residual thermal energy [kWh/week]	0	0	0	0
Full load operating hours [h/week]	6	6	6	168

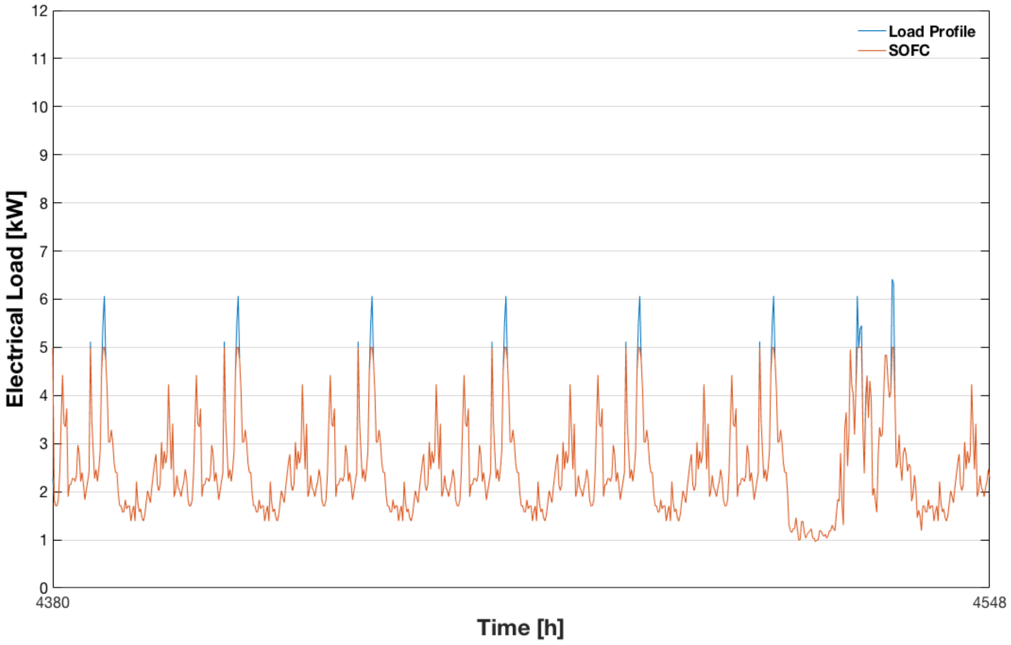


Figure 5-52: System configuration E1-A (Summer) – Electrical load

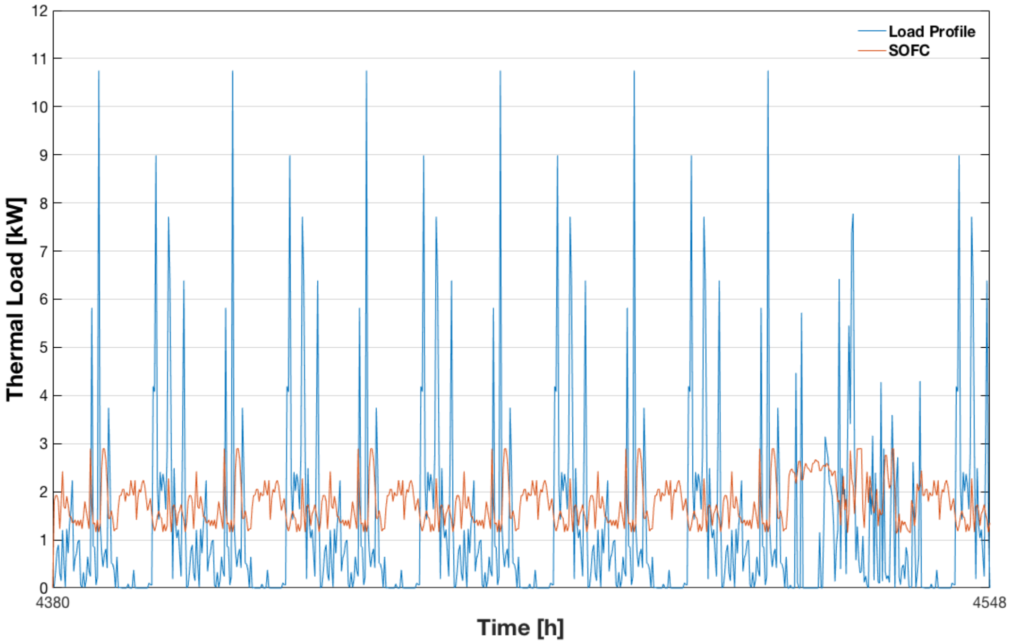


Figure 5-53: System configuration E1-A (Summer) – Thermal load

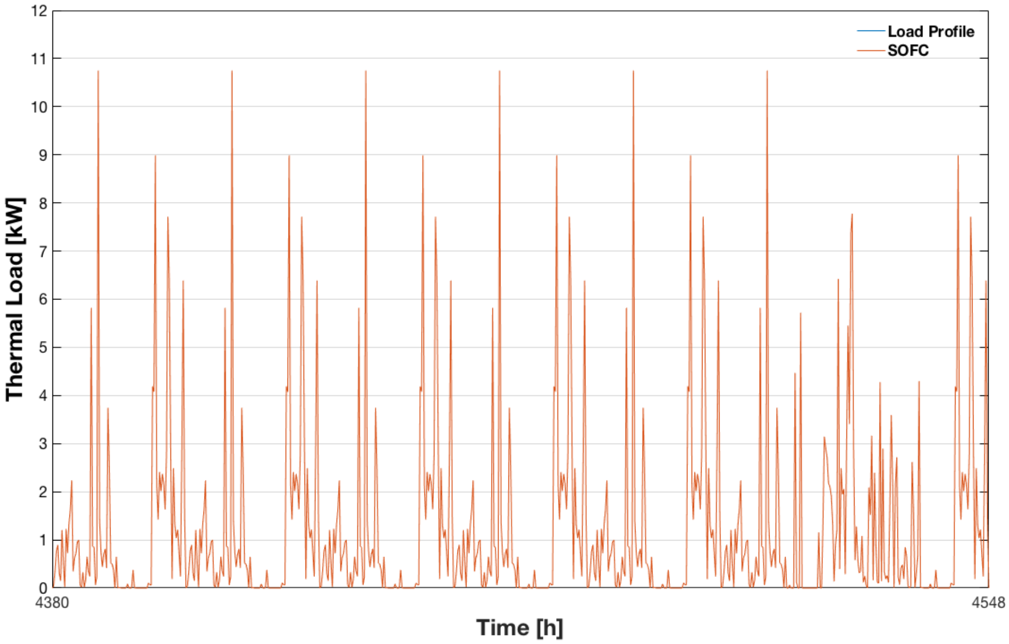


Figure 5-54: System configuration E1-A (Summer) – Thermal output (storage)

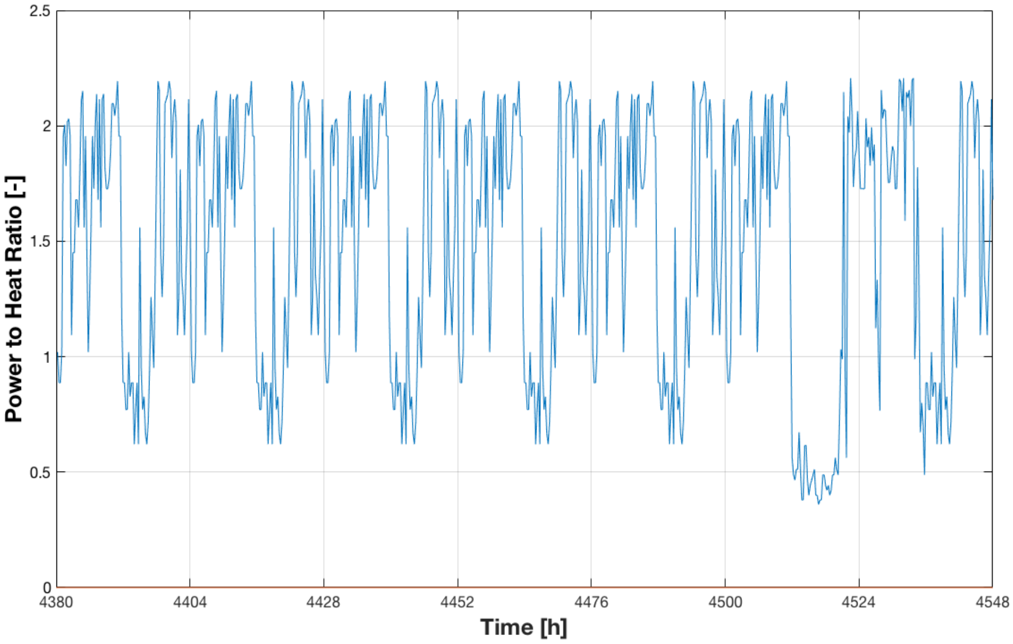


Figure 5-55: System configuration E1-A (Summer) – Power to heat ratio (Production)

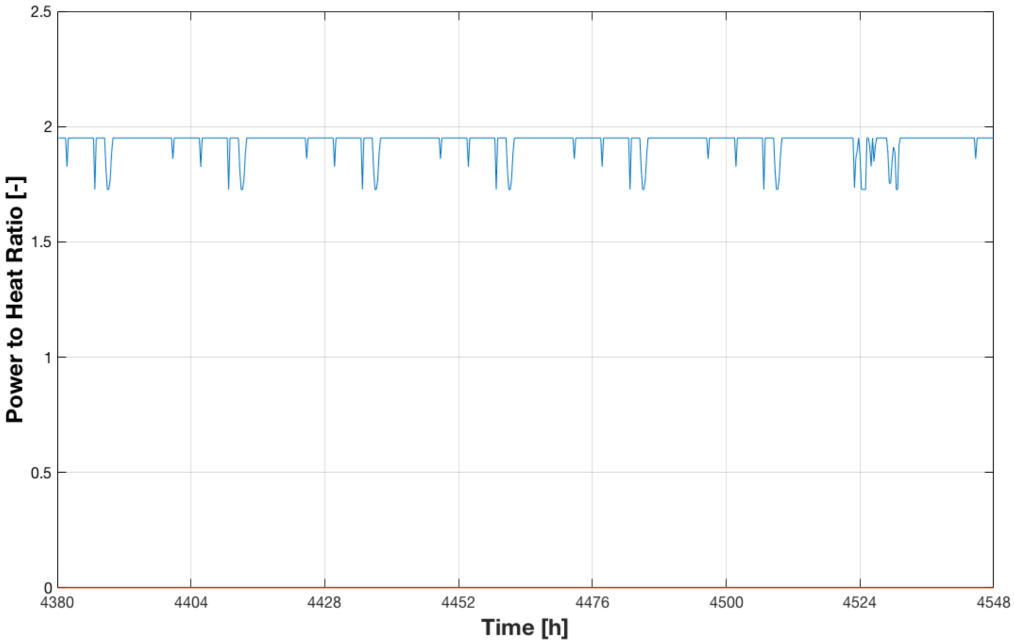


Figure 5-56: System configuration E1-C (Summer) – Power to heat ratio

The results for system configuration E1 show very good electrical and thermal cover ratios for all operational modes in summer. Nevertheless, operational modes A, B and C only present very little full load hours. The amount of surplus produced electrical energy raises from operational mode A to D.

Table 5-54: Results for system configuration E2 (Summer)

Parameter	**System E2-A**	**System E2-B**	**System E2-C**	**System E2-D**
Electrical output [kW]	10	10	10	10
Operational mode [% load]	10 – 100	50 – 100	75 – 100	100
Power to heat ratio [-]	0,16 – 2,2	2,1 – 2,2	1,90	1,75
Electrical cover rate [%]	100	100	100	100
Thermal cover rate [%]	100	100	100	100
Electrical power demand [kWh/week]	104	104	104	104
Thermal power demand [kWh/week]	52	52	52	52
Surplus electrical energy [kWh/week]	2	430	846	1.266
Surplus thermal energy [kWh/week]	32	195	435	765

Residual electrical energy [kWh/week]	0	0	0	0
Residual thermal energy [kWh/week]	0	0	0	0
Full load operating hours [h/week]	0	0	0	168

The results for system configuration E2 show full coverage of the electrical and thermal load profile for all operational modes in summer. Nevertheless, operational modes A, B and C only present very little full load hours. The amount of surplus produced electrical energy raises from operational mode A to D. The SOFC system with the power output of 10 kW produces more additional energy than the 5 kW system. Additionally the 10 kW system operates barely at 100 % load if operating in load following mode. During summer the 10 kW system seems to be oversized for this application.

Table 5-55: Results for system configuration E1 (Winter)

Parameter	**System E1-A**	**System E1-B**	**System E1-C**	**System E1-D**
Electrical output [kW]	5	5	5	5
Operational mode [% load]	10 – 100	50 – 100	75 – 100	100
Power to heat ratio [-]	0,45 – 2,20	1,75 – 2,20	1,75 – 1,90	1,75
Electrical cover rate [%]	95	95	95	95
Thermal cover rate [%]	16	13	10	26
Electrical power demand [kWh/week]	111	111	111	111
Thermal power demand [kWh/week]	471	471	471	471
Surplus electrical energy [kWh/week]	1	66	226	417
Surplus thermal energy [kWh/week]	0	0	0	0
Residual electrical energy [kWh/week]	20	20	20	20
Residual thermal energy [kWh/week]	1.559	1.624	1.520	1.372
Full load operating hours [h/week]	11	11	11	168

Thermal output of the gas fired heating unit for full coverage of thermal load profile [kW]	18 – 19	19	18	17

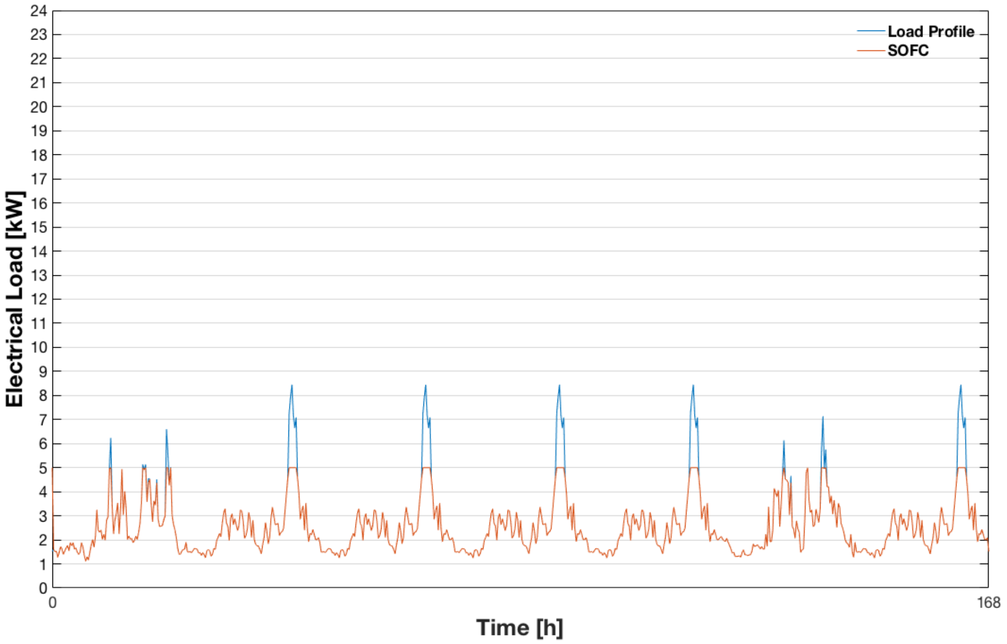


Figure 5-57: System configuration E1-A (Winter) – Electrical load

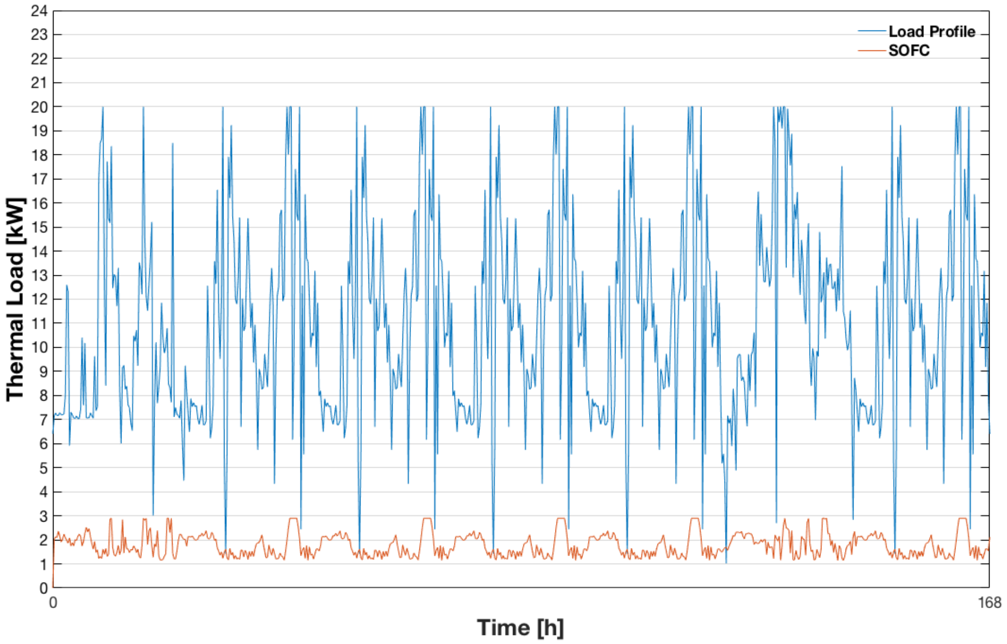


Figure 5-58: System configuration E1-A (Winter) – Thermal load

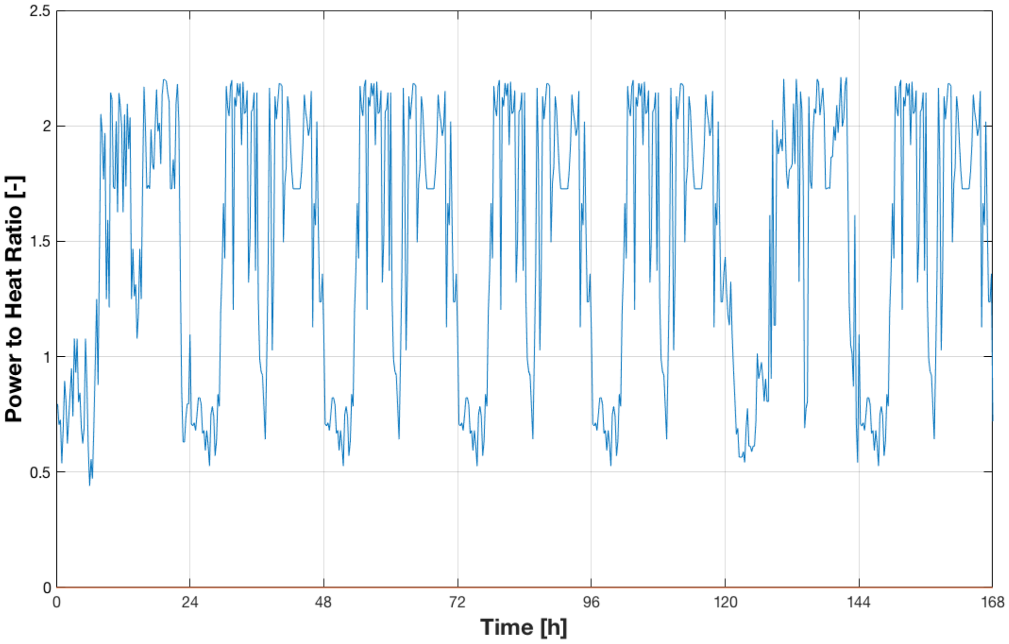


Figure 5-59: System configuration E1-A (Winter) – Power to heat ratio

In winter all the different operational modes present very good cover rates for the electrical, but not for the thermal load profile. As a result a gas fired heating unit with a specific thermal power output is necessary in order to cover the full thermal load. The electrical cover rate is also below 100 %. Full coverage can be achieved by implementing a SOFC system with larger power output or by buying additional energy from the grid. These factors combined with achievable prices for feed-in to the grid determine when the operational mode has to be changed.

Table 5-56: Results for system configuration E2 (Winter)

Parameter	System E2-A	System E2-B	System E2-C	System E2-D
Electrical output [kW]	10	10	10	10
Operational mode [% load]	10 – 100	50 – 100	75 – 100	75 – 100
Power to heat ratio [-]	0,25 – 2,20	1,85 – 2,20	1,85 – 1,95	1,75
Electrical cover rate [%]	100	100	100	100
Thermal cover rate [%]	44	21	35	52
Electrical power demand [kWh/week]	111	111	111	111
Thermal power demand [kWh/week]	471	471	471	471

Surplus electrical energy [kWh/week]	2	419	821	1.238
Surplus thermal energy [kWh/week]	0	0	0	0
Residual electrical energy [kWh/week]	0	0	0	0
Residual thermal energy [kWh/week]	1.049	1.466	1.211	887
Full load operating hours [h/week]	0	0	0	168
Thermal output of the gas fired heating unit for full coverage of thermal load profile [kW]	18	18	16	14

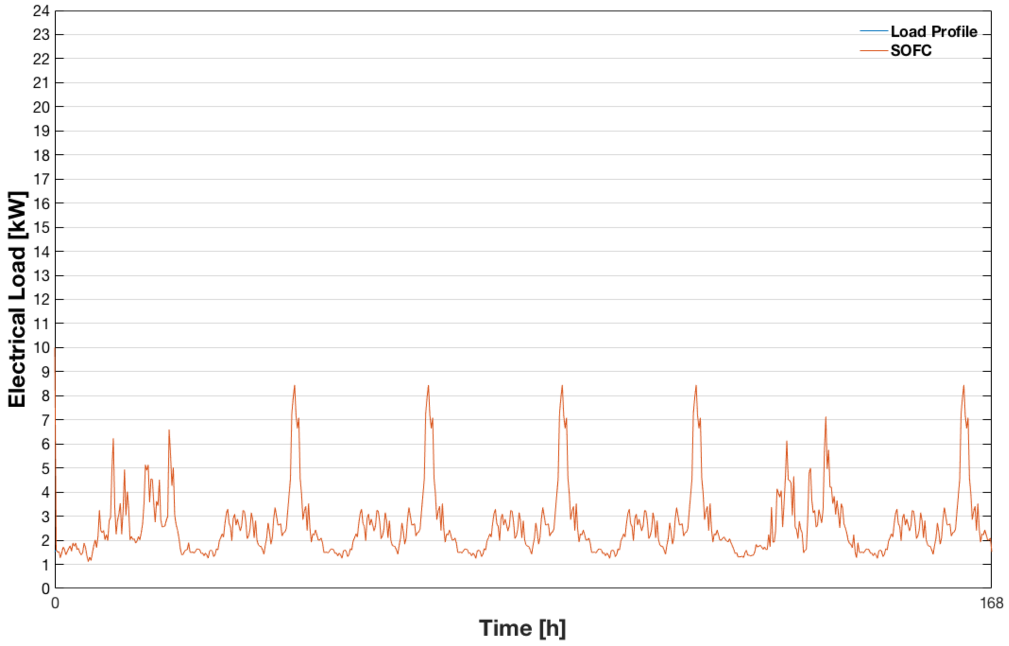


Figure 5-60: System configuration E2-A (Winter) – Electrical load

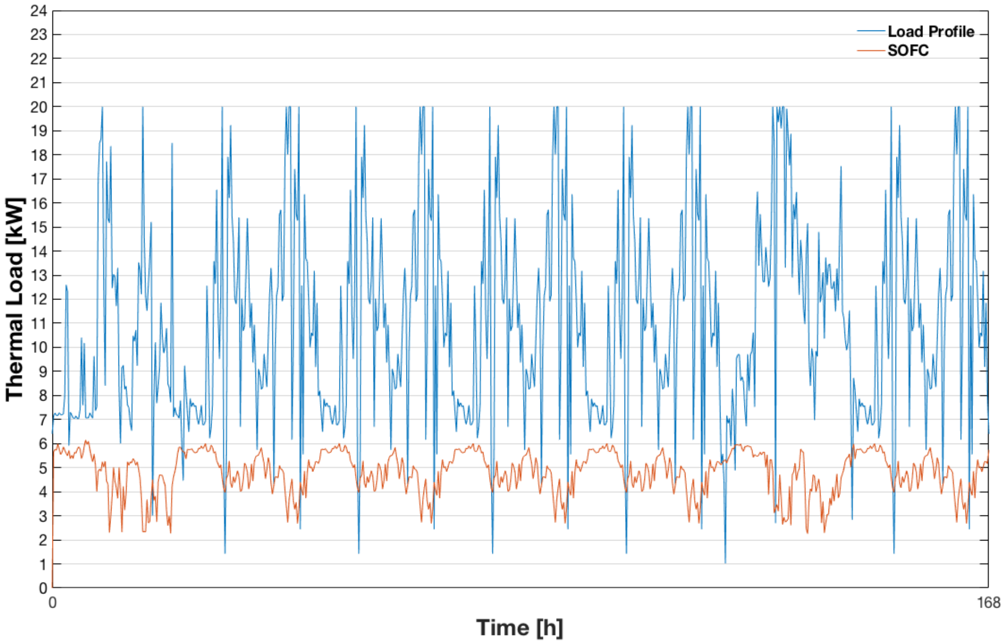


Figure 5-61: System configuration E2-A (Winter) – Thermal load

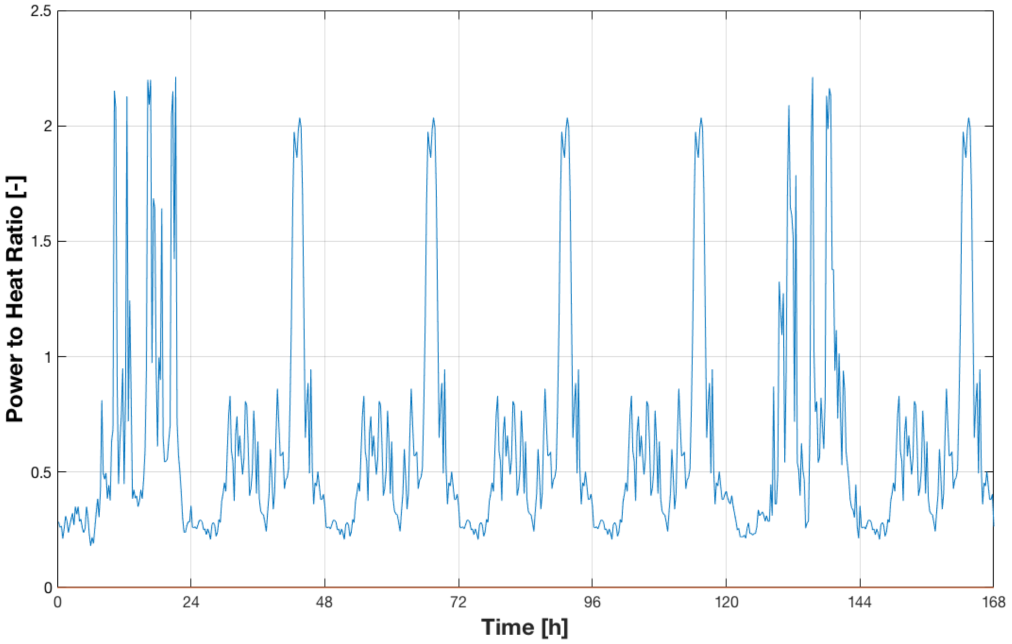


Figure 5-62: System configuration E2-A (Winter) –Power to heat ratio

Because the different power to heat ratios of the 10 kW system the thermal cover rates are higher than the ones of the 5 kW system. Furthermore, the gas fired heating unit needs a little less power output in order to cover the full thermal load profile.

As a result, the larger 10 kW system is also not able to cover the full thermal load profile. Therefore, the smaller 5 kW system plus a gas fired heating unit in winter is a economical reasonable option for this application. Therefore, the 5kW system configurations seem to be the optimal solution for this application for summer and winter. Nevertheless, all load following system configurations show only very little full load hours which leads to longer amortization periods.

5.5 Residual load profile

In order to determine the suitability of SOFC systems to cover residual loads the following simulation has been conducted. Therefore, a residual load profile has been compiled by downscaling the combination of multiple industrial load profiles minus the energy supply of wind, photovoltaic and biomass. A typical current residual load profile (Today) is compared to a prospective load profile (Future). The considered time range is a full year while the following figures represent a typical week in summer and winter.

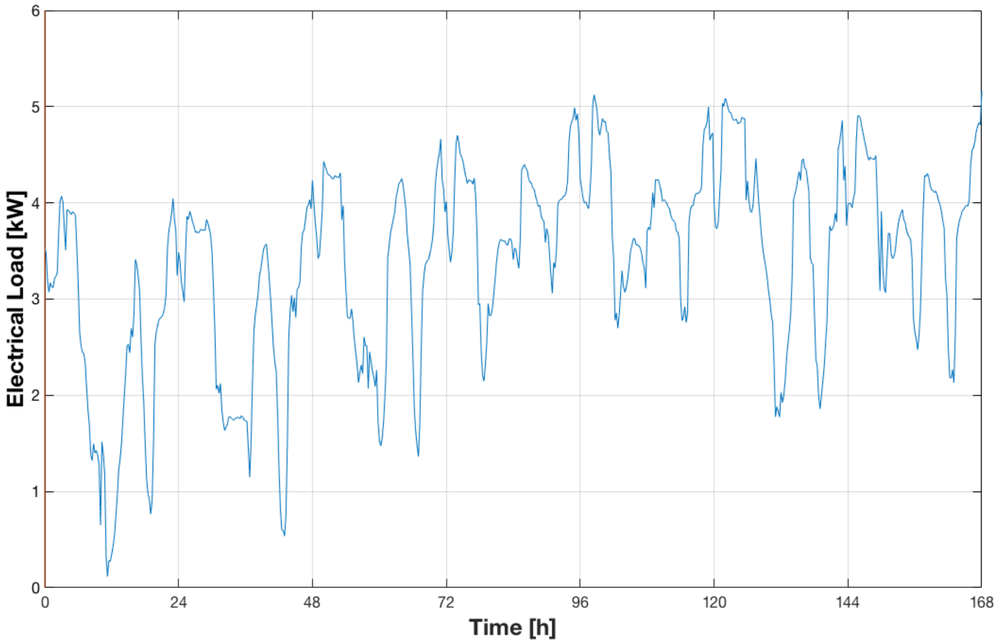


Figure 5-63: Residual load profile (Today)

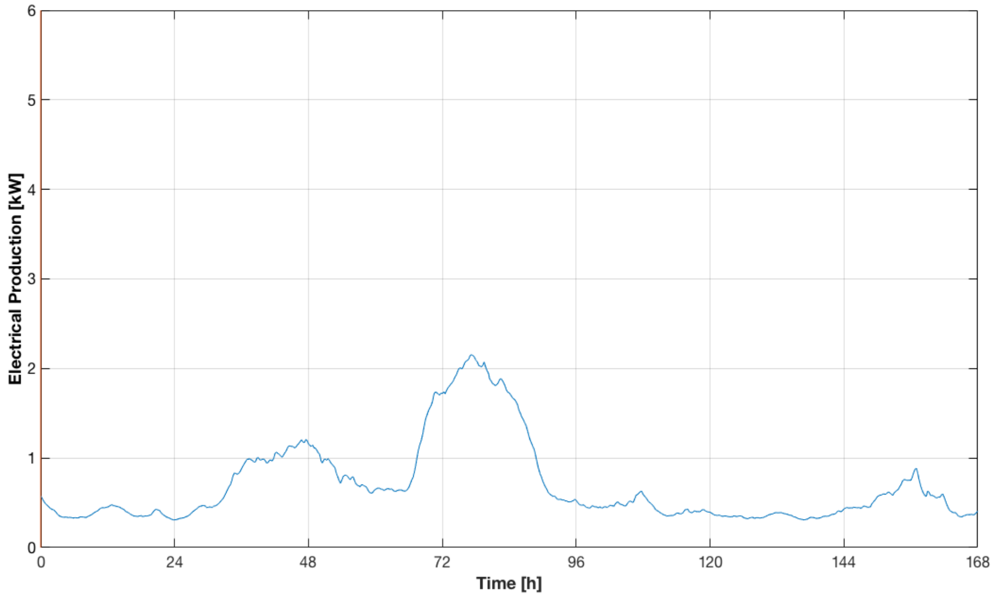


Figure 5-64: Photovoltaik, wind and biomass electrical production (Today - Winter)

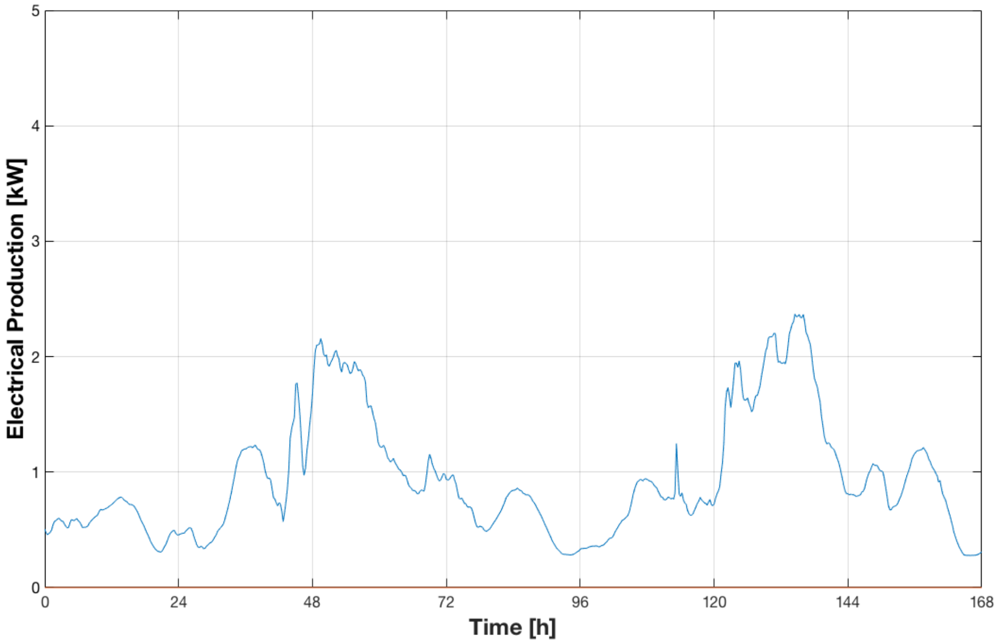


Figure 5-65: Photovoltaik, wind and biomass - Electrical production (Today - Summer)

In order of checking the suitability of a SOFC to cover residual loads the following strategy has been applied:

- Strategy F:
    - <u>Aim:</u> Full coverage of the residual electrical load profile
    - <u>Operational mode:</u> Electricity controlled
    - <u>Method:</u> Testing of different system outputs and operational modes

Table 5-57: System configuration F1

	System configuration F1
Nominal electrical power [kW]	5
Stack temperature [°C]	830
Operational mode A [% load]	0 – 100
Operational mode B [% load]	50 – 100

Operational mode A covers the full load range of 0 – 100 % load. This operational mode leads to high losses in electrical efficiency below 50 % load. Nevertheless, this operational mode is intended to ensure full coverage of the residual load profile. Operational mode B tests the suitability of a SOFC to cover residual loads while operating thermally self-sustaining between 50 – 100 % load.

Table 5-58: Results for system configuration F1 (Today - Winter)

Parameter	System F1-A Winter	System F1-A Summer	System F1-B Winter	System F1-B Summer
Electrical output [kW]	5	5	5	5
Operational mode [% load]	0 – 100	0 – 100	50 – 100	50 – 100
Positive electrical cover rate [%]	99	99	99	99
Positive electrical power demand [kWh/week]	113	113	113	113
Surplus positive electrical energy [kWh/week]	0	2	63	83
Negative residual load [kWh/week]	> 1	> 1	> 1	> 1

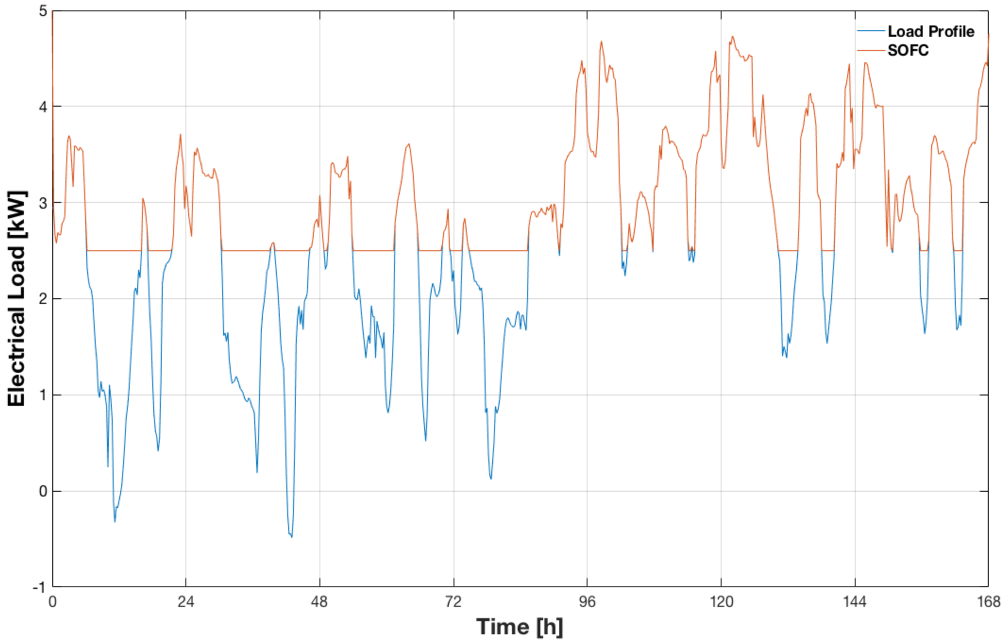


Figure 5-66: System configuration F1-B (Today - Winter) –Electrical load

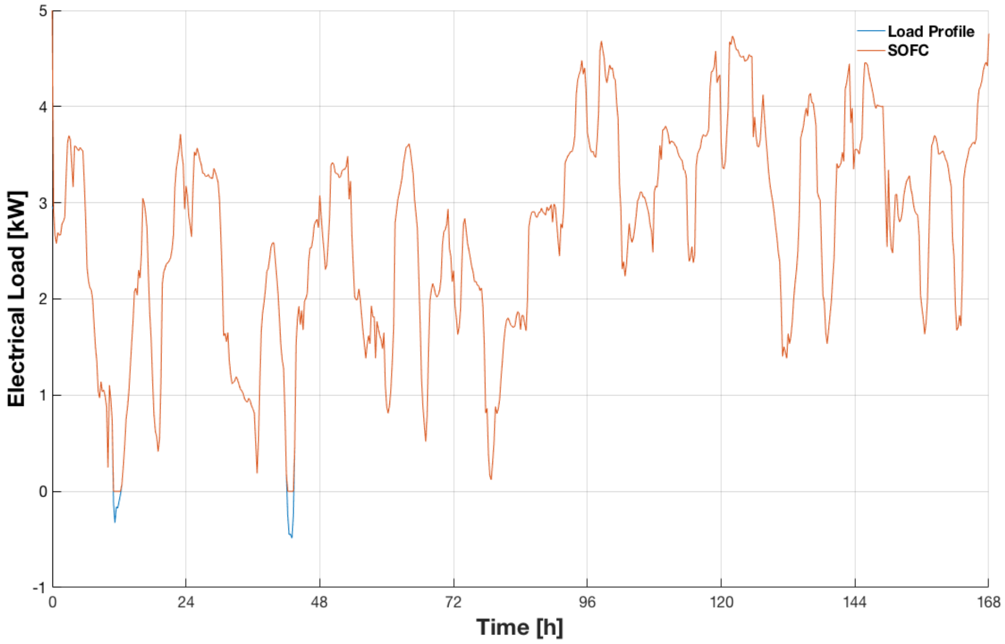


Figure 5-67: System configuration F1-A (Today - Winter) – Electrical load

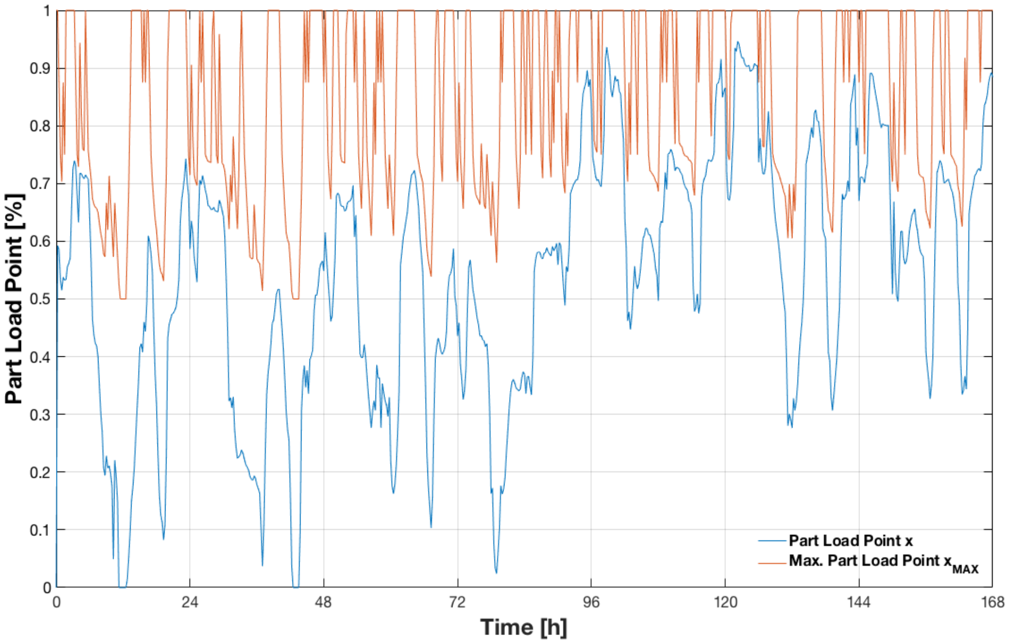


Figure 5-68: System configuration F1-A – Partial load point

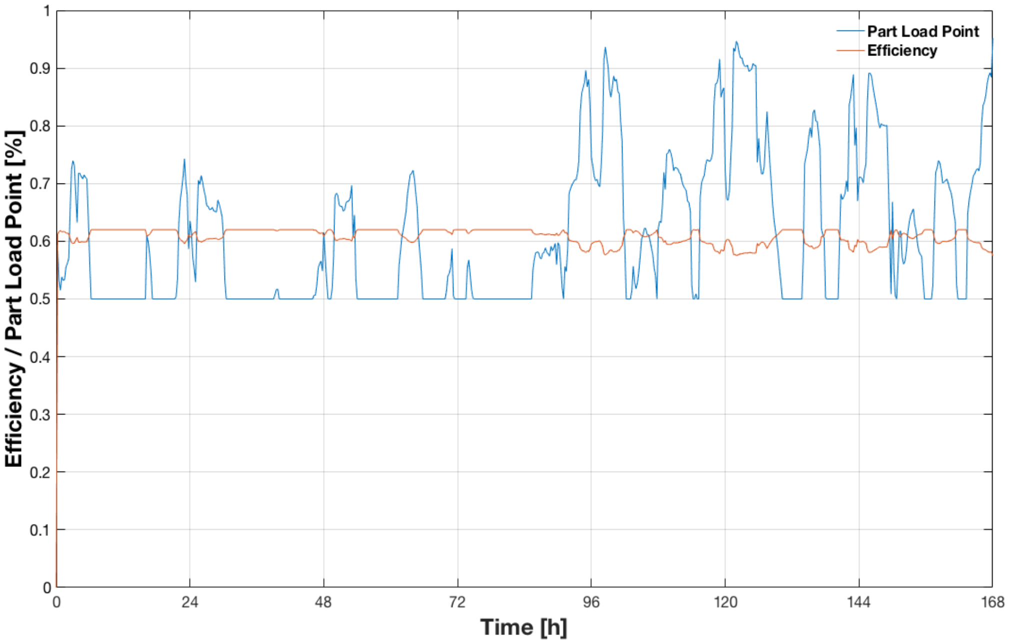


Figure 5-69: System configuration F1-B (Today - Winter) – Efficiency / Part load point

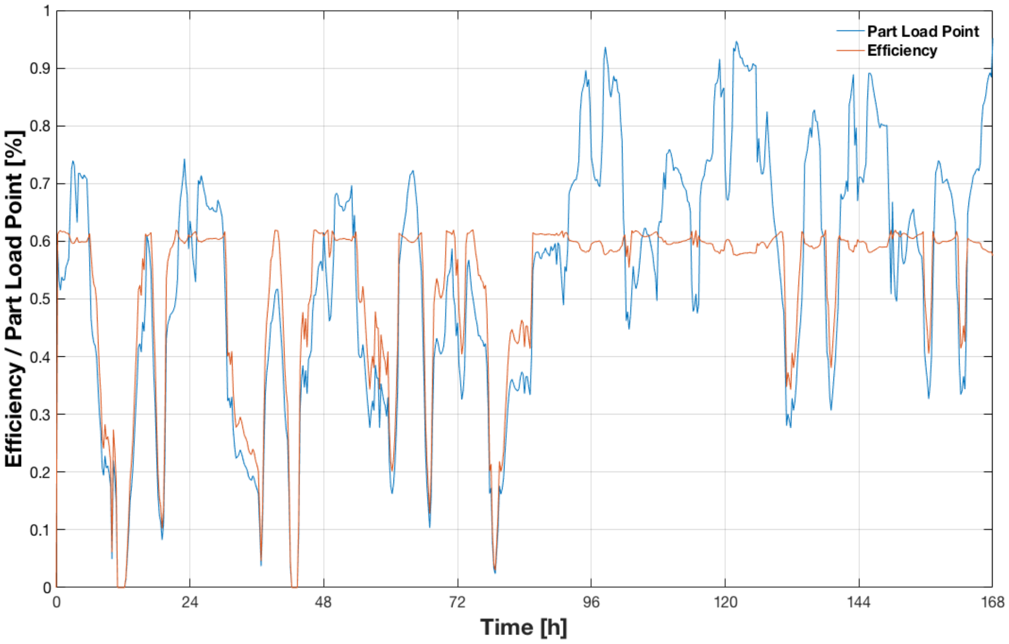


Figure 5-70: System configuration F1-A (Today - Winter) – Efficiency / Part load point

In summer and in winter all the different operational modes present very good cover rates for the electrical load profile. Nevertheless, operating between 50 – 100 % load results in the production of a large amount of surplus energy. The negative residual load cannot be covered completely. Although the electrical load profile is strongly fluctuating, the maximal achievable part load point remains high enough so that the SOFC can cover the load profile (*Figure 5-68*). Changing the operational mode to 0 – 100 % load leads to major electrical efficiency losses (*Figure 5-70*).

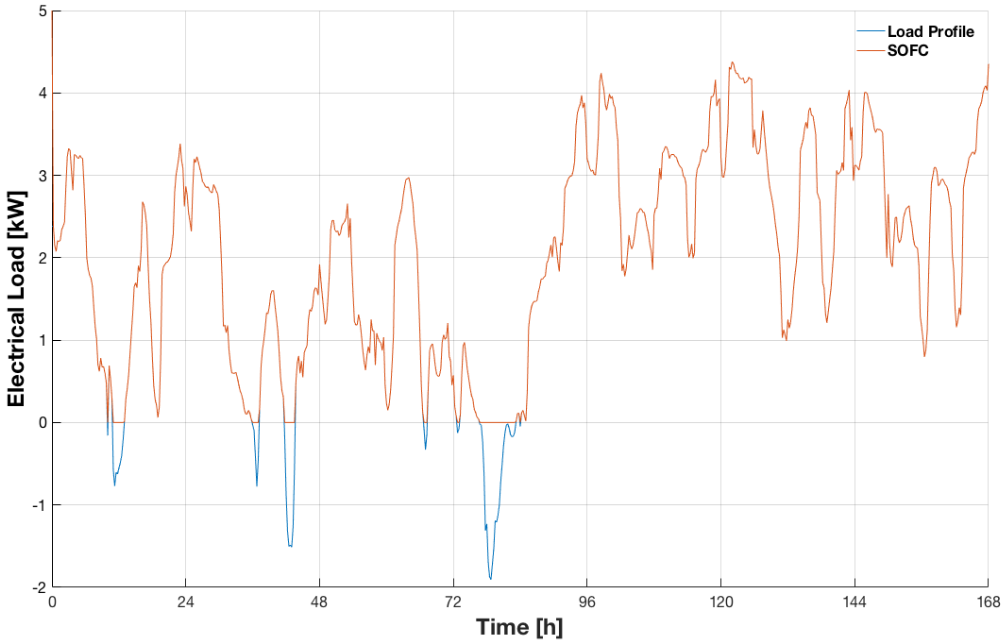


Figure 5-71: System configuration F1-A (Future - Winter) –Electrical load

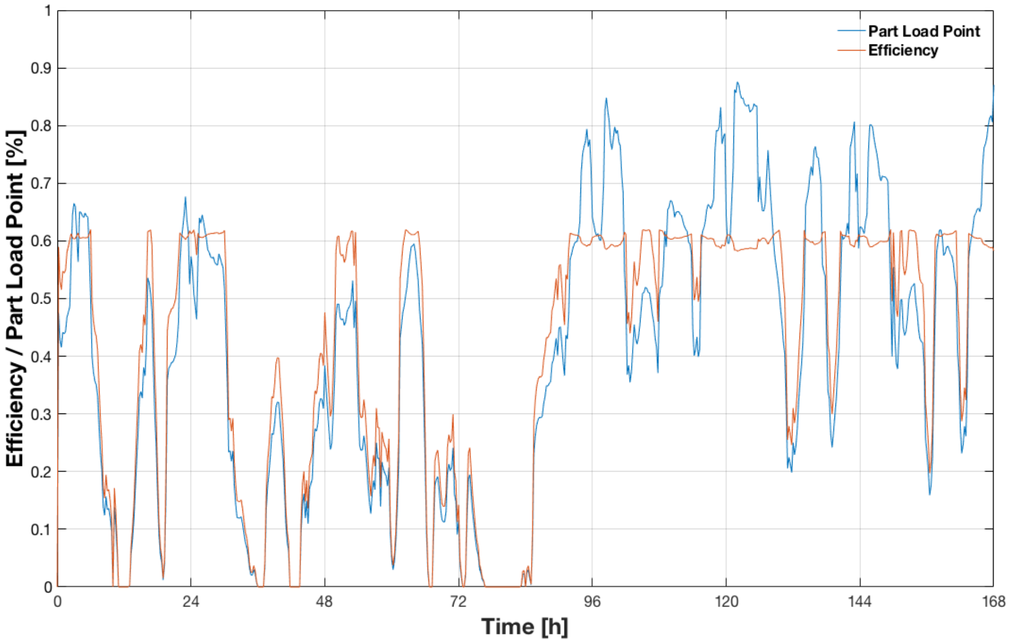


Figure 5-72: System configuration F1-A (Future - Winter) – Efficiency / Part load point

Table 5-59: Residual loads comparison - Today / Future

Parameter	Today	Future
Positive electrical cover rate [%]	99	99
Positive electrical power demand [kWh/week]	113	84
Surplus positive electrical energy (Operation mode B) [kWh/week]	16	34
Negative residual load [kWh/week]	> 1	3

Future residual load profiles will present an increased amount of negative residual loads as a result of ongoing growth in the renewable energy sector. Therefore, a residual load profile has been compiled by downscaling the combination of multiple industrial load profiles minus an increased amount of wind, photovoltaic and biomass energy supply. While the cover rate of the positive electrical load profile stays constant, the increased amount of negative residual energy leads to efficiency losses as well as not coverable negative loads. Additionally, more surplus energy is produced for operation mode B.

6 PROFILE OF REQUIREMENTS

Performance comparison

Compared to commercial reference technologies, SOFCs present major advantages regarding electrical efficiency, emissions and maintenance efforts. Nevertheless, additional development, especially on the fuel cell stack is necessary to improve performance degradation rates, initial costs and scalability. While SOFC CHP systems can compete with gas turbines and engines in most of the residual comparison parameters, especially the start-up time and ramp rates are very depended on the specific application. Continuous operation, prime with additional feed-in to the grid, island as well as supply of control energy are possible applications for SOFC CHP systems. However, every single application needs a very specific system configuration and operational mode in order to fulfill the technical and economical requirements. Especially emergency backup applications are difficult because of the very slow start-up times of the system.

Control energy

SOFCs present adequate ramp-rates while operating at high stack temperatures. Therefore, the technology should be able to pass the technical prequalification requirements for the supply of control energy. In order to supply control energy combined with an industrial application SOFC CHP systems must operate above 75 % load while remaining at the maximal stack temperature. This operational mode ensures sufficient ramp-rates as well as required power output reliability. The self-adjusting minimal temperature is the limiting factor for these applications. Scaling up the nominal output of the systems accomplishes different operational load ranges.

Industrial and residential

SOFC CHP systems are also suitable for industrial and residential power and heat generation applications. While operating in the preferred electricity controlled mode, the electricity demand as well as the thermal base load can be covered completely. Residential applications benefit from the generously adjustable power to heat ratio in order to cover the seasonal load profile. Still, a large amount of surplus electrical energy for feed-in to the grid or local energy storage is produced. In order to cover the whole thermal power demand, a large amount of thermal energy is necessary. This energy can either be provided by an additionally added gas fired heating system or by external sources. Choosing a combination of multiple SOFC systems, the static and dynamic load following system combination obtains the best results. The actual system configurations depend on the specific requirements of the system operator and can lead to conflicts regarding electrical and thermal cover ratio, surplus produced energy and full load hours.

Table 6-60: Design parameters

Parameter	**Electrical cover ratio**	**Cover ratio of thermal base load**	**Full load operating hours**	**Surplus energy**
Electricity controlled	high	high	less	low
Heat controlled	high	high	more	high
Dynamic systems	-	lower	less	higher
Dynamic + static system	-	higher	more	lower
Power output at min. demand	low	-	more	low
Power output at max. demand	high	-	less	high

Residual load

In order to cover residual load profiles, the spread between the maximal and the minimal required power can lead to a conflict with the systems optimal operational mode > 50 % load. Changing the operational mode to 0 – 100 % load leads to major electrical efficiency losses. Future residual load profiles will present an increased amount of negative residual loads as a result of ongoing growth in the renewable energy sector. This will negatively influence the performance of SOFCs.

7 SUMMARY, CONCLUSION AND FUTURE PROSPECTS

In order to specify the requirements for SOFC CHP systems as controllable power plants of the future a technical and economical comparison and a simulation model were compiled.

The comparison between SOFC CHP systems, gas turbines and gas engines is primarily based on literature and internet research as well as various discussions with AVL List GmbH experts. Compared to commercial reference technologies SOFCs present major advantages regarding electrical efficiency, emissions and maintenance efforts. Nevertheless, additional development, especially on the fuel cell stack is necessary in order to improve the overall performance of the SOFC. As a result, the technology should be able to compete with commercially available technology in additional applications.

The model was designed in MathWorks MATLAB and consists out of multiple scripts and functions. Furthermore, several Microsoft Excel sheets are included which interact with the code in a way to enable calibration of the model by high dynamic process analysis. The aim of the model is to determine optimal SOFC CHP system configurations and operational modes for specific applications with load profiles as input parameter. In the model the supply of control energy and the combined production of electricity and heat for industrial and residential applications were simulated. The results show various combinations of possible SOFC CHP system configurations in order to meet the specific requirements of the different applications as well as the limits of the technology. The major complications occurred are on the basis of the varying stack temperature which sets limits to the start-up time, ramp-rates and reliability of power production. Nevertheless, the results show the suitability of SOFCs for multiple applications, although minor compromises regarding electrical and thermal cover ratio, surplus produced energy and full load hours are often indispensable.

The model can easily be adapted with the calibration sheets. As a result, different technologies like gas engines and gas turbines can be simulated and compared to SOFC CHP systems. The results of the simulations can further be used for an economic analysis of SOFCs. The surplus produced energy as well as the additional needed energy can be valuated with prices, which can influence the total costs of ownership.

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