# INNO-SOFC Deliverable D2.1

## End-user & application analysis

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# 1 INTRODUCTION

## 1.1 Research objectives Task 2.1

The main objective of this work package is to identify the most promising applications and end users for stationary SOFC systems. This information will be used in system design and validation and also to focus dissemination and exploitation activities.

## 1.2 Targets of the FCH JU

The FCH JU states that it is necessary to improve competitiveness and prepare for the commercialization of fuel cell products for distributed CHP applications in intermediate power range. The tender therefore requires the following product properties compared with state of the art (SoA) in 2014:

- Improved electrical efficiency by min. +10% points, reaching 57% for SOFC technology
- Higher than 82% total energy efficiency by improved thermal integration
- Improved stack lifetime in system operation from SoA by 50%, reaching >30,000h
- Improved design, manufacturing and supply chain to reduce product cost by 30%
- Improved maintenance interval by 100%, reaching 2 years of operation without planned shut down

The specific challenge of the INNO-SOFC project is to develop, manufacture and validate new generation fuel cell system technologies with lower cost, maintenance need and extended lifetime. This topic also requires development of value chains and innovative business models to enable market uptake. Work Task 2.1 is one of the deliverables addressing this point.

## 1.3 WP2 and Work Task 2.1

Work Package 2 is divided into three work tasks. Task 2.1 is focused on defining the optimal application of the C50 fuel cell system Task 2.2 contains an analysis of future trends and their effect on SOFC application, and finally Task 2.3 focuses on the techno-economic analysis of SOFC systems. This deliverable contains the report for Task 2.1: End-user and application analysis.

Today, SOFCs are mainly used to produce heat and power, but more can be done. Horticulture for example, needs electricity for lighting, heat, CO2 and water, all of which can be produced in a SOFC system. And the SOFC can provide prime power to users with a backup power requirement. Energy Matters and Convion will perform application analysis and profitability mappings taking into account i.e. energy prices, by-products, operation and maintenance costs, system life-time, and investment costs. Special focus will be given on specific boundary conditions for each application (regulations, size and interface limitations, load profile, etc.). In addition, integration possibilities with e.g. heat storage and heat pumps will be analyzed. Some application areas to be studied are:

- Built environment: Hospitals, hotels, shopping malls, apartments
- Industry and public facilities: food, chemical, waste water treatment plants
- Agriculture and horticulture: manure digesters, greenhouses

## 1.4 Scope

The scope is geographically defined by the EU27 countries, due to the availability of Eurostat data. The following boundaries are also defined:

- The system described in the report is the Convion C50 fuel cell
- The time horizon for cost calculation is 2020

# 2 METHODOLOGY

The most important part of this study is to determine the net value for different users & applications. As can be seen in Figure 1, the Convion C50 SOFC fuel cell can generate a lot more value than just electricity and heat. This chapter contains a description of the cost and value drivers that are used to assess the value of the C50 fuel cell system and explains how these values are calculated.

## 2.1 Cost and value drivers

A technical and conceptual review of the system has led to a long list of possible values. Not all values can be capitalized, it will depend on several factors such as: the final technical configuration, the country and application chosen and the cost of CO2. In Figure 1 is shown which drivers might be applicable.

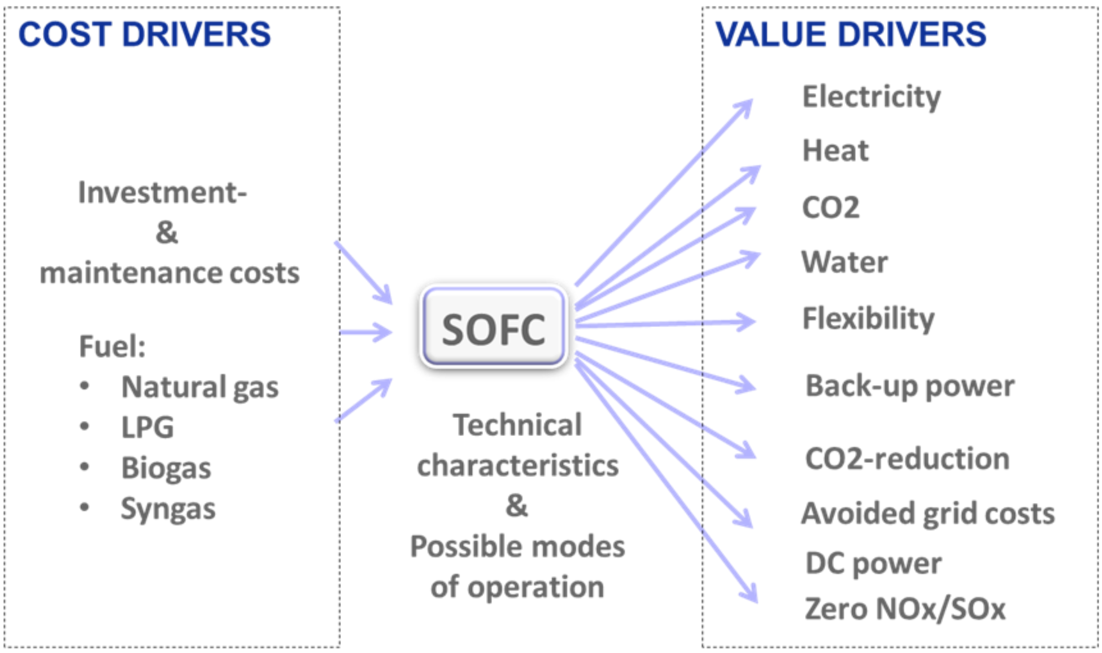



*Figure 1: overview cost and value drivers*

The corresponding monetary values and costs are described in Chapter 7.

### 2.1.1 Description of value drivers

**Electricity**

Electricity produced for consumption on-site is likely the most important value driver. Therefore, the electrical efficiency is of great importance. The high electrical efficiency is one of the key benefits compared to the performance of gas engines. Electricity prices for chosen country and relevant sectors from Eurostat will be used for the analysis, including subsidies where relevant.

**Heat**

Low temperature heat from the cooling circuit of the fuel cell (<80 degrees), can be used. The standard configuration provides up to 20 kW of heat, this can be increased to 25 kW if a lower return temperature of 40 degrees can be achieved. The value for heat is equivalent to the gas price for the chosen country.

**Useful $CO_2$**

Preliminary measurements show that the exhaust gases of the fuel cell can be used in energy intensive agriculture to substitute liquid $CO_2$. The measurements show almost no detectable quantities of carbon monoxide, NOx, SOx or fine particles. A pilot plant will be necessary to provide more understanding of the real-time emissions and how to use the system coupled to a greenhouse.

**Energy Label upgrade**

For new buildings, the SOFC can upgrade the energy label. For energy efficient buildings, it can reduce the amount of extra insulation or solar PV needed, reducing the primary energy consumption of the building. If the SOFC runs on biogas, then the system can count as renewable energy production as well (for Near Zero Energy Buildings). For the analysis, it is assumed that the SOFC avoided investment in solar PV (1000 €/kW) for the equivalent CO2 savings. For this study we assume that one C50 fuel cell system has the $CO_2$ reduction capability of 1000 solar panels.

**Lower contracted grid capacity and kW max**

A reliable generator can lower the contracted capacity for the client. Values from the Dutch grid operators will be used. Clients also pay for the highest power consumption in a month, called the kW max.

**Subsidy for renewable electricity (when using biogas)**

In some countries, a subsidy or green certificate or feed-in tariff for renewable electricity can be obtained.

**Continuous power and prime power**

A study by the Aberdeen Group estimated that companies lose an average of $138,000 for every hour their data center is offline. For a bank this can be $6 million per hour. In hospitals it is used to power the operating room and HVAC. Ergo: clients want to pay for reliability. The SOFC can replace a diesel generator or even a UPS system, depending on the required reliability and system configuration. Besides saving on generator and UPS costs, clients are willing to pay for reliability in their system. The value will depend on the user, we assume the following (see Paragraph 6.1.5):

- Omitting a diesel generator: 8500 €/y value
- Omitting a UPS: 9700 €/y value
- Increased reliability: 14400 €/y value

**DC electricity**

The SOFC can provide DC electricity. For certain applications, like data centers or new greenhouses, this can really be advantageous. The first advantage is that no inverter is needed. Assuming a 5 year life and 10.000€ investment costs, this is an important saving. The standard voltage in Europe will likely be 350V and multiplications thereof, but the US and Japan are moving to 380V / 760V[1].

[1] Direct Current BV, 2014 – Direct Current: the future of direct current in the Netherlands

For example, in new greenhouses, a 700V DC grid for lighting can replace a 400V 3-phase AC grid, potentially saving up to 2000 kg of copper per hectare. Also, energy savings of 5-10% are achieved due to avoided conversion losses in horticulture and data centers. Claims have been made about longer lifetime of light fixtures and other equipment.

**Avoided NOx emissions in low NOx zones**

The C50 product is a power generator which utilizes fuel energy efficiently without generating any local emissions such as $SO_x$, $NO_x$, VOC or particulate emissions. During testing, the NOx values were below the detection limit.

Being able to generate electricity without significant NOx emissions can provide value in certain situations. A gas engine would need a Selective Catalytic Reduction (SCR) unit in order to meet the NOx standards. The avoided SCR cost can be used as a value driver.

**CO2 emission reduction**

The C50 reduces primary energy use and therefore CO2 emissions related to electricity generation. Whether this has a positive effect depends on the local situation in each country. At the current power rating this will not be applicable for all end-users, however energy companies that fall under the European Emission Trading Scheme (ETS for short) for CO2 might profit from the C50 in smart grid CHP mode in their production portfolio.

Moreover, some countries have specific certificates that either value the portion of carbon free produced electricity from CHP (CHP certificates) or value the emissions per user (white certificates).

**Production of clean demi water**

The SOFC produced clean water, which can be mixed with minerals and used in horticulture. We assume 1€/m3, this can be higher in some countries.

**Avoided grid enhancement in urban areas**

The SOFC can provide additional electrical capacity to the grid, reducing the need for local grid enhancement or larger power transformers, providing savings for the Distribution System Operator (DSO) or for end-users that want to have a larger electrical capacity.

**Balancing services**

If a customer has high inductive load, reactive compensation can be applied. In some countries, the pricing of kVArs is based on the highest monthly peak, for example in Finland. Here, kVArs are invoiced on monthly basis based on the peak value subtracted by 20% of the peak active power value.

A SOFC could generate up to 50kVar*5€/kVarpeak*12 months/year = 3000€ per year savings (based on tariffs in Finland). The fuel cell system could then provide reactive power during peak hours and true power during the rest of the day.

An alternative to deliver reactive power would be a capacitor banks. Capacitor banks are relatively cheap: 1600$ for 140 kVArs, so it is not likely that a fuel cell will save much cost here.

In other countries, for example the Netherlands, you have to pay a fee for all kVArs/h you consume. This fee is much lower than the electricity price, making it not profitable to produce reactive power.

**Providing flexible capacity**

The SOFC can modulate between 50% and 100%. There is no local market yet for local grid support/flexibility. An SOFC is not suited for supplying primary control reserve, but it might be able to supply secondary control reserve. The required ramp rate (in the Netherlands) has to be >7%/min. The C50 has demonstrated this capability during tests. An aggregator is needed, where some players aggregate smaller power units down to 100kW. The value of secondary control reserve is limited.

### 2.1.2 Cost drivers

The C50 has three main cost drivers during a project:

1. Investment costs. These include stacks, Balance of Plant, installation costs. Possibly also civil cost (ground, building) and a gas compressor.
2. Operation & maintenance cost. These include also stack replacement.
3. Fuel Cost. These vary significantly per EU country, with different fiscal regimes and commodity prices.

## 2.2 Description model

In order to determine for which applications the Convion system has the highest added value an extensive model has been built to calculate user & country specific business cases.

The model consists of four pillars

1. Country specific input
2. Inventory of 50+ applications
3. Inventory of user requirements.
4. Technical specifications

The longlist of applications and user requirements has been compiled with data from previous projects around CHP (source i.e. CODE2 project), literature and research performed within this project. In Figure 2 the model is visualized.

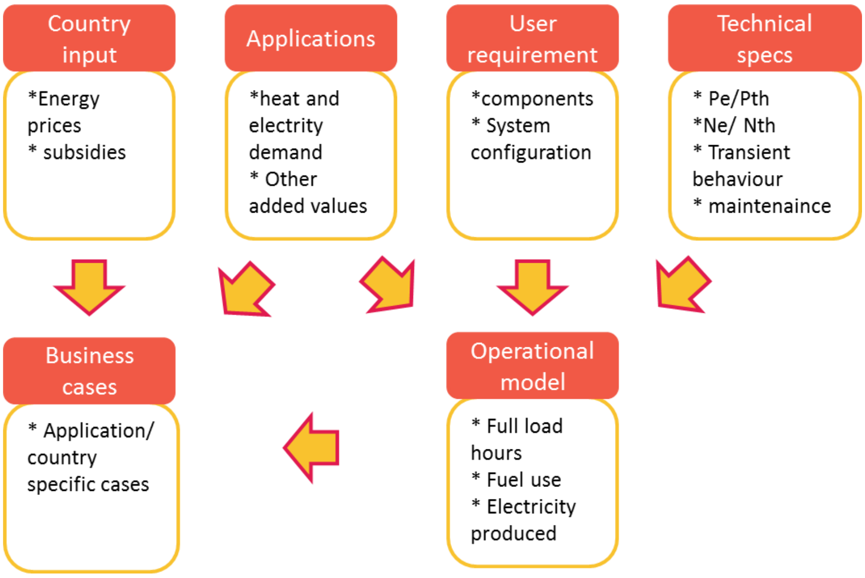



*Figure 2: Model suitable applications INNO SOFC*

The output dashboard calculates the business case based on the chosen country, end-user type (commercial/industrial) and system configuration (USPs, heat pumps, desiccant wheels etc. etc.). This resulted in a short list of most suitable applications.

# 3 DESCRIPTION CONVION C50

## 3.1 Technical characteristics

The general system lay-out or setup is shown in Figure 3.

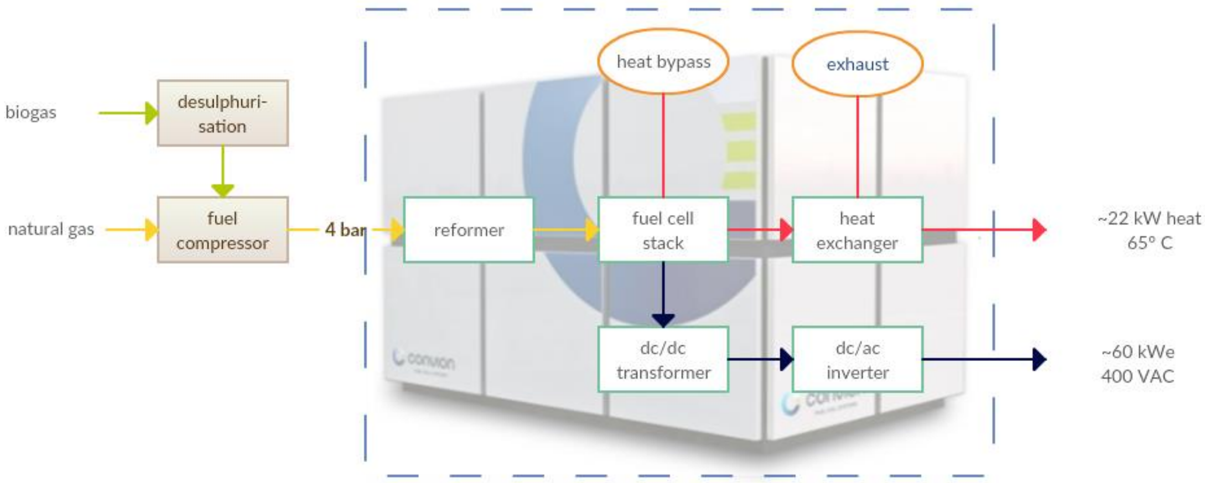



*Figure 3 – general system setup*

The fuel cell provides efficient and reliable power while realizing significant environmental benefits. The unique advantages are listed below:

- Simplicity
  - No moving parts in anode circulation
  - No liquid water
  - Minimized purge gas need
  - Only one discrete heat exchanger
- Flexibility
  - Fuel flexibility (NG / BG / Dual Fuel)
  - Stack flexibility
  - Modular design, own IPR in core
  - Indoor / outdoor operation
- Performance
  - Efficiency 60%
  - Total efficiency 80-85% with built-in CHP option
  - Island, transient and part load operability
  - Low emissions

The SOFC system specifications are shown in Table 12.

| System specifications | |
|---|---|
| Maximum electric AC power (kW) | 60 |
| Nominal electric power (kW) | 60 |
| Thermal power (kW) | 20-25 |
| Electrical effiency | 60% |
| Degradation effect (%/1000 hours) | 0.5% |
| Startup characteristics | 24h cold, 2 kW/min hot |
| Part load characteristics | 50%, 2 kW/min |
| Fuel flexibility | Yes |
| Dimensions (meters) | 2x2,6x2,3 |
| Weight (kg) | 4 000 kg |

*Table 1 – SOFC system specifications*

**Emissions**

The C50 can be regarded as a zero emission technology regarding NOx, SOx and fine particles. The flue gas emissions of the C50 are very low and significantly lower than current EU thresholds.

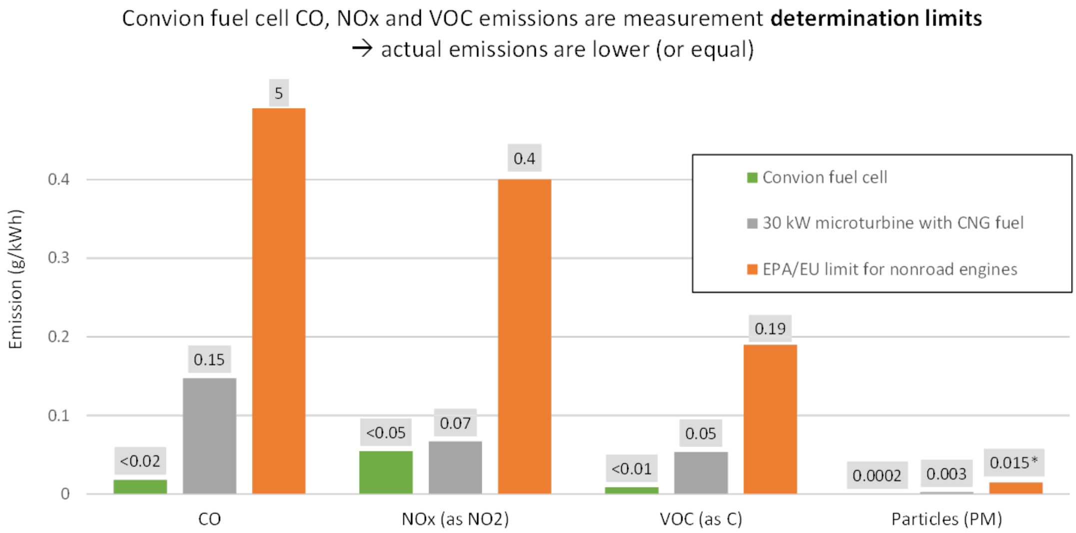



*Figure 4: Comparison SOFC emissions*

- Comparison of Convion fuel cell (nominal operation point) emissions with micro turbine and EPA/EU limits
- Micro turbine VOC emission and EPA limits for VOC include non-methane hydrocarbons (NMHC) only
- EU limit for nonroad engines is for hydrocarbons (HC)
- VOC emission determination limit for Convion fuel cell includes methane (but none detected)

## 3.2 Modes of operation

The C50 has five different operating modes – off mode, heating and loading mode, hot standby mode, cooling mode and failure mode. These modes are described in Figure 5.

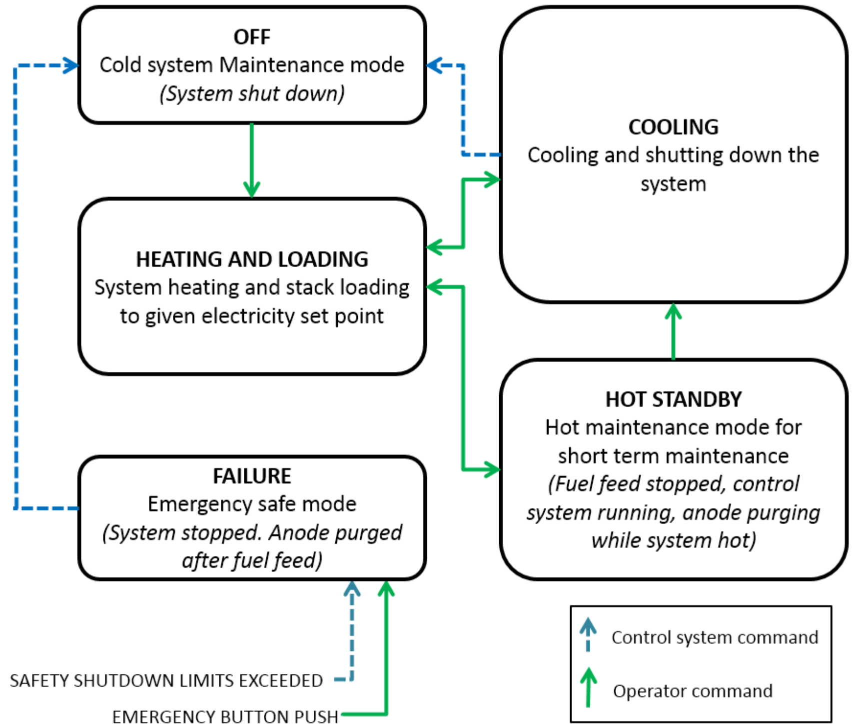



*Figure 5: C50 system modes of operation and transitions between modes.*

**Start-up**

Start-up is initiated by an operator command to instigate a mode transition from off mode to heating and loading mode. System heat-up is carried out by circulating electrically heated air while heating up the fuel cell stacks and system. At a pre-determined temperature minimum fuel flow needed for maintaining necessary thermal and chemical conditions in the system is initiated. The heating continues until the fuel cell stacks reach approximately 700 °C. Then electrical loading of the stacks is ramped up while increasing fuel feed. Figure 4 illustrates negative efficiency of the system at start-up mode, when electrical heating is used for heating up the system. Heat-up of a cold system to full load takes over 24 hours.

**Normal operation**

In normal operation the system is kept at as steady conditions as possible, regulating the air feed according to measured stack temperatures. In normal operation, loading of the system is based on operator set point.

**Modulated normal operation**

By nature, a high temperature fuel cell system is best suited for steady loading and has a limited load following capability due to thermal inertial of the stacks. Maximum stack current ramp up/down rate is 4% of total range per minute.

**Temporary hot stand-by**
Due to long heat-up times and a preference to avoid thermo-cycling of the system, an operator may choose to take the system to a hot stand-by mode for example to facilitate short term maintenance actions that require disconnection of fuel flow. Upon request to transfer to stand-by mode, system current is first ramped down to zero similarly to cooling mode. Once zero loading has been reached, fuel feed is stopped and replaced by a feed of safety gas to maintain a protective atmosphere at the stacks. During a short term hot-stand by, system cools down passively but does not experience a full thermocycle and can be brought back to full power relatively quickly.

**Emergency Shutdown**
In case of a gas alarm or other failure preventing normal operation or shutdown, the emergency shutdown sequence is triggered. In this case cathode air feed is discontinued, cathode air feed valves closed and the fuel system is flushed for a predefined time with nitrogen. The system then cools down passively without any feed. In case of a gas alarm all non-ex equipment in the process module is de-energized and the SOFC stacks in the stack module are disconnected from the DC/DC converters. Ventilation of the process module continues approximately 12 hours by means of an explosion safe suction blower with power backup.

## 3.3 Installation options

Due to the systems characteristics (i.e. size and weight), the SOFC will likely be placed outside in many occasions.

**Outdoor characteristics**

- \+ Simple gas safety, natural ventilation, no monitoring need outside system, less or no interface with building automation needed.
- \+ exhaust can be let out in free air
- \+ easier maintenance access, e.g. no height limitations, easier to take system for off-site maintenance
- \+ no room ventilation requirements
- \+ average temperatures may be lower than in indoor, less need to ventilate e.g. power electronics, improves lifetime of fans and components
- \+ No concerns regarding back-flow of exhaust in an system stop situation (as opposed to indoor where a negative pressure in the room may cause reverse flow through the air system
- \- Unit has to withstand all weather conditions, higher IP-class requirement, higher corrosion resistance required
- \- Freezing conditions must be handled properly, requires cabinet heaters for cold start-up
- \- Maintenance actions are also subject to the weather
- \- Direct sunlight may cause high temperatures inside the system

The following ambient conditions are applicable:

| Ambient conditions | |
|---|---|
| | |
| Seismic vibration | IBC 2003: Site class D |
| Rain | IP54 |
| Temperature [°C] | -20 … +45 |
| Altitude [m] | 0 … 1000 |
| Ambient humidity [RH-%] | 0 … 99 |
| Installation | Indoor / Outdoor |

*Table 2: Ambient conditions for the C50*

## 3.4 Maintenance

Convion SOFC systems operate autonomously according to a given set-point, without operator intervention. The systems also monitor their operative condition and assure safety and continuity of power supply. Required preventive maintenance tasks can be divided into on-site maintenance tasks that can be carried out by operators and those requiring action by authorized service personnel. In addition to the on-site activities, fuel cells and fuel pre-reformer catalysts require scheduled replacements. These system refurbishment activities are carried out off-site due to their invasive nature. Listing of the main preventive maintenance categories and refurbishment tasks with approximate intervals are shown in Table 3. None of the on-site tasks require system cooling.

*Table 3 Preventive maintenance and system refurbishment activities of Convion C50 fuel cell systems.*

| Type of activity | Preventive Maintenace | Weekly | Bi-annual | Annual | 3-5 years |
|---|---|---|---|---|---|
| Remote | General check-up of system condition | • | | | |
| On-site maintenance by operators | Replacement of cathode air intake filters | | • | | |
| | Replacement of ventilation air filters | | • | | |
| | Gas clean-up adsorbent switch-over | | • | | |
| | (Optional) gas compressor oil exchange | | • | | |
| | ESD gas bottle check-up/ replacement | | • | | |
| On-site maintenance by authorised service personnel | Air blower maintenance | | | • | |
| | Scheduled sensor & actuator replacements | | | | • |
| | Meter calibration check | | | • | |

| Type of activity | Refurbishment | | | | 3-5 years |
|---|---|---|---|---|---|
| Off-site by authorised manufacturing or service personnel | Reformer catalyst replacement | | | | • |
| | Fuel cell stack replacement | | | | • |
| | | | | | |

### 3.5 Possible system configurations

#### 3.5.1 CHP operation

An SOFC system is suited for baseload heat and power production. Thermal power and total efficiency depend on the water circuit that is connected to the fuel cell, see Figure 6. Total efficiencies greater than 85% can be achieved by cooling the exhaust to 70°C or lower.

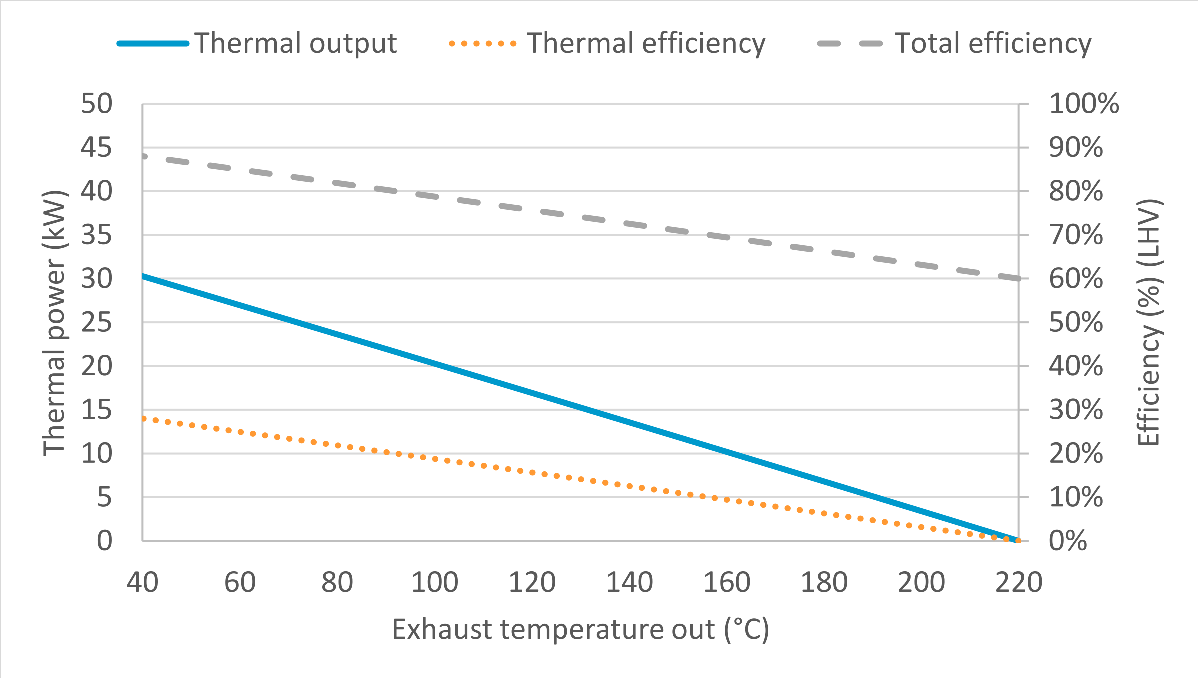



*Figure 6 – Total system efficiency related to thermal output and exhaust temperature*

By cooling down the exhaust, the thermal efficiency and therefore overall efficiency increases. Normally the temperature trajectories depend on the specific heat appliance. For floor heating the temperature trajectory could be as low as 35/25° C, which is much more advantageous. The system would have to be adjusted to handle condensation.

Figure 7 compares revenues for cooling to 80° C versus cooling to 50° C.

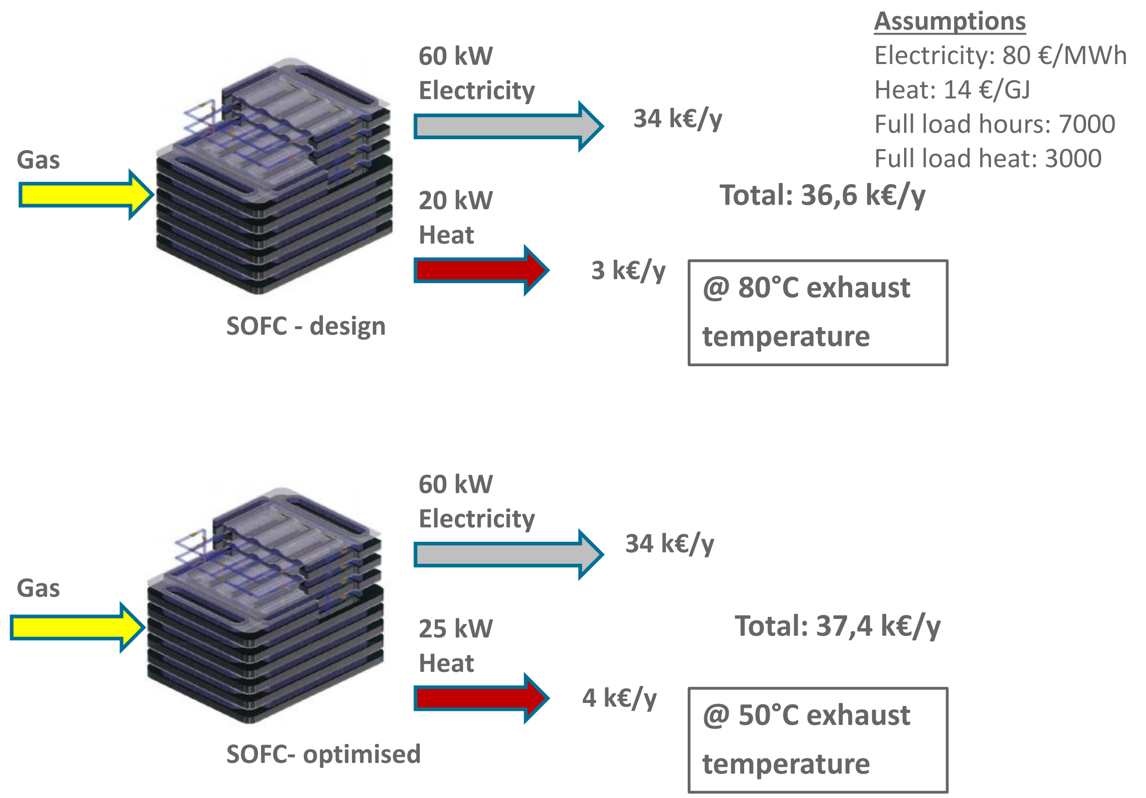



*Figure 7 – yearly revenue of SOFC system for design CHP operation mode and optimized for heat utilization by increased effective heat exchanger (HEX) surface.*

The advantage is an increase in revenues by 2-3% and the selling point of approximately 5% higher total efficiency.

### 3.5.2 Heat pump combinations

The C50 produces a flow of warm air which might be utilized in an air source heat pump. Several combinations with heat pumps have been regarded. Even though this may not be the most elegant configuration with regard to physics (exergy). In practice, the costs for heat are relatively high compared to their exergy value.

A heat pump can be used for extracting the currently unused heat from the flue gas, which serves as an alternative for the previously described increased HEX surface. This heat pump configuration is shown in Figure 8.

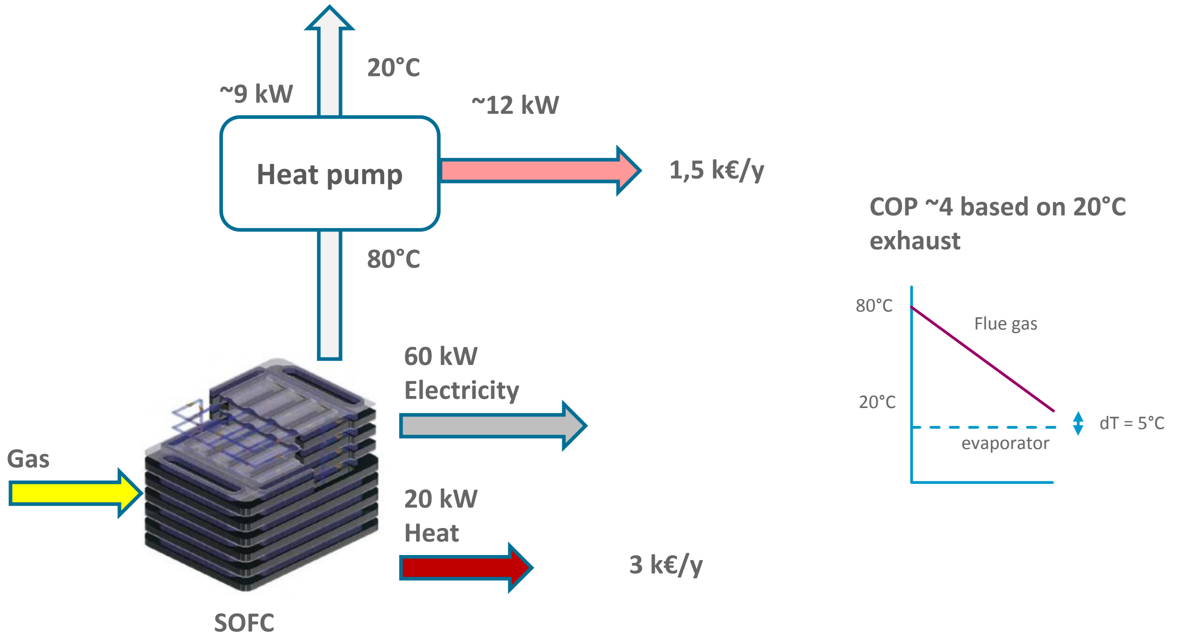



*Figure 8 - heat pump combined with SOFC system; heat pump heat source is the remaining heat in the flue gas of the SOFC system*

For determining the revenue, a COP (coefficient of performance) of 4 has been assumed which is based on the evaporation temperature of 15°C, as shown in the graph on the right, and standard supply temperature of 55°C.

$$COP = \eta_{tot}\left(\frac{T_H}{T_H - T_L}\right)$$

Where $T_H$ is the condenser temperature (in Kelvin), which is the supply temperature plus approximately 5°C for the pinch temperature. The total efficiency $\eta_{tot}$ for a heat pump is typically 60%, somewhat lower for small systems and a bit higher for larges systems. This includes compressor efficiency since this is a relatively small system the efficiency will be a bit lower, typically 55%. This results in a COP of approximately 4.

Simply using the electricity of the SOFC for the heat pump is not advantageous because an absorption heat pump has the same function but the investment is much lower.

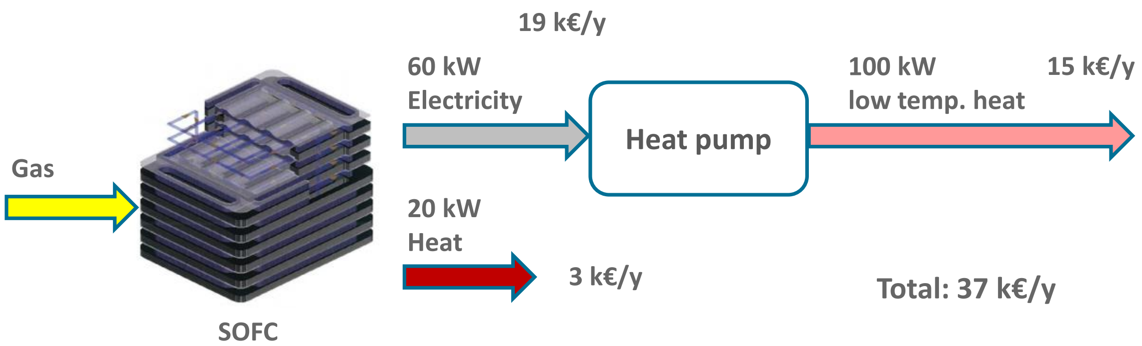



*Figure 9 – heat pump combined with SOFC system; electric feed of heat pump supplied by SOFC*

The system as depicted in Figure 9 adds complexity but no extra value is created.

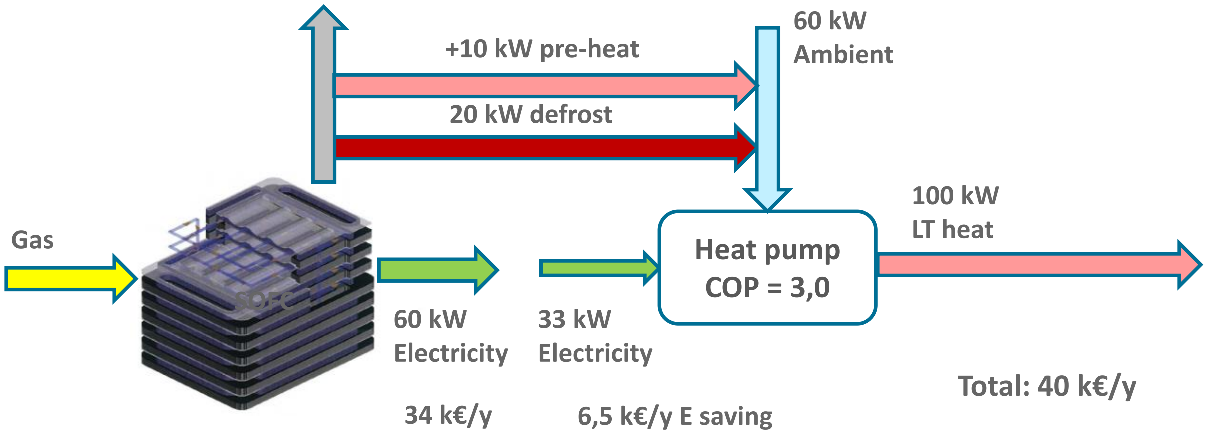



*Figure 10 – heat pump integrated with SOFC system; increasing heat pump efficiency (COP) by utilizing heat of SOFC system for avoiding the defrost cycle and including pre-heating of the heat pump evaporator*

By utilizing the heat of the SOFC for the defrosting cycle and increasing the COP of the heat pump by preheating the ambient air, which if fed to the heat pump, electricity use of the heat pump is reduced. This adds complexity but also increases the revenue. However, in accordance with the second law of thermodynamics, heat produced at low temperatures is less valuable than at high temperatures. In practice low temperature heat means a larger heat transfer area and thus a higher investment. Assuming a value reduction of 20% due to the lower temperatures, the economic profit vanishes.

### 3.5.3 Prime power

Although the Inno SOFC system is primarily designed for grid parallel operation, the system can provide load following capability with certain limitations in grid-independent mode. In grid independent operation, the system controls its output capacity based on demand and employs an internal dissipative buffering mechanism allowing for instant response to load fluctuations within a certain window below the instantaneous output capacity. The instant response capability window extends 0-20kW downward from the peak instantaneous output capacity. E.g. if the system operates at 45kW output point, it has an ability of instantly responding in the range of 25-45kW. Instant response to demands below this range is also facilitated, however with the effect of subsequently shifting the dynamic response window by reducing the peak output capacity correspondingly. E.g. if in the previous situation, the load drops to 15kW, the system output capacity is reduced such that the response window is thereafter 15-35kW. The system continually adjusts its operating point so that the average load is in the middle of the response window.

The system cannot provide instant response to demands exceeding its instantaneous output capacity. In response to demand exceeding the instant response capability, voltage and frequency of the output AC waveform will droop to limit the power output. The output capacity is then increased towards the peak output capacity with the nominal ramp rate of the system, i.e. within minutes to tens of minutes. The currently defined load increase ramp rate is conservative and can be significantly increased through control optimization.

In many cases, the above described load following capability described above is alone sufficient for the application needs. Further flexibility can be met by including an energy storage as buffer capacity. Such capacity can be installed in parallel with the fuel cells within the SOFC system, or as an independent unit on the AC side. Example configurations are presented below.

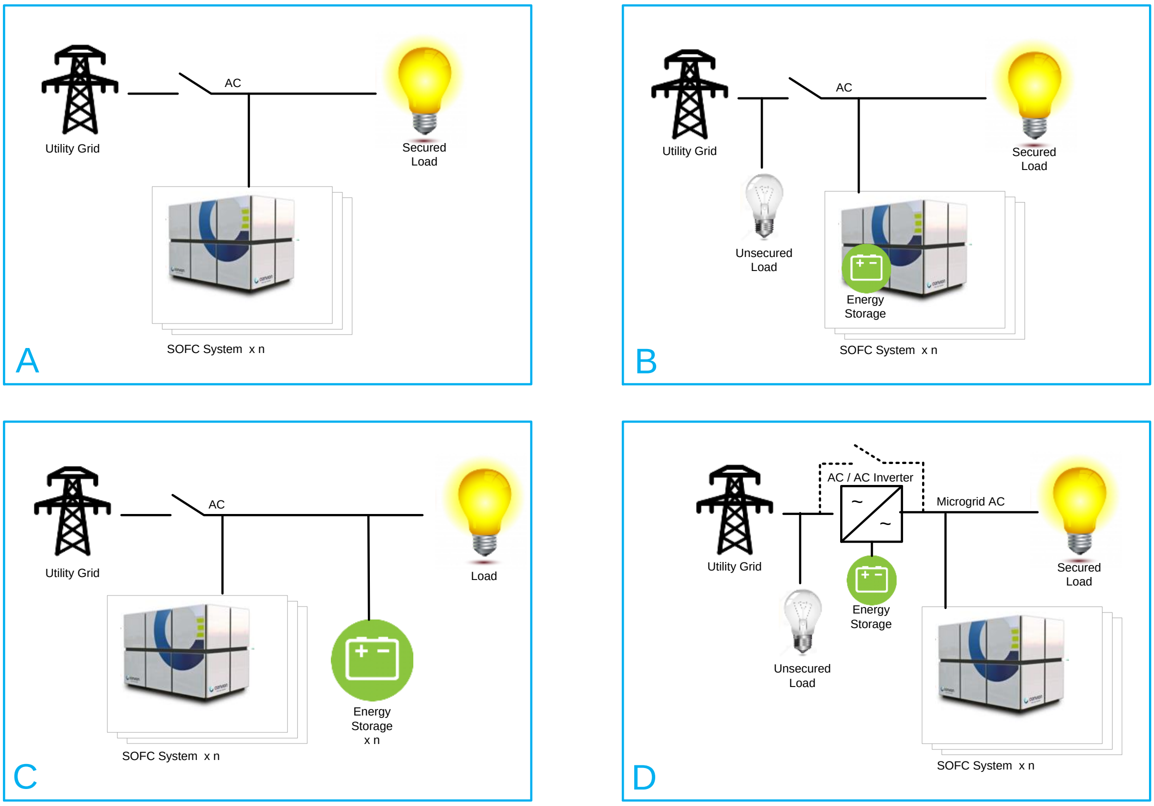



*Figure 11: Comparison different prime power configurations*

Configuration A represents the simplest and lowest cost topology in which SOFC systems are installed in parallel with the existing grid, and the grid connection is equipped with disconnecting means. In this topology, the grid fault condition will be visible to the load until disconnection takes place, where after transient capability in grid-independent operation is limited by the SOFC capabilities as described above. This configuration provides the added value of power security with minimum added cost.

In configuration B, the transient response capability in microgrid mode has been improved by equipping the fuel cell systems with an internal energy storage. A single inverter is shared between the fuel cell and the energy storage. Thus, the fuel cell has unlimited transient response capability up to the peak capacity of the inverter.

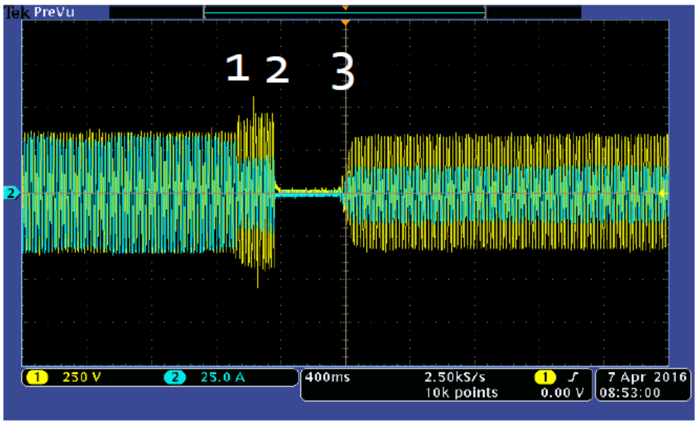
In topology C, the energy storage is arranged as independent units interfacing with the microgrid. In microgrid mode the energy storage responds to voltage and frequency changes in the microgrid, thus complementing the capabilities of the SOFC. This configuration provides the flexibility to tailor the SOFC and energy storage capacities independently to the application needs.

In example configurations A-C there is a direct utility grid connection whereby grid failures will be visible to the load until grid disconnection takes place. In configuration D, this has been overcome by adding an AC/AC inverter in the grid connection. This inverter can isolate the microgrid voltage and frequency from the utility, thereby providing absolute power security to the load. The inverter can be equipped with a solid state bypass switch to minimize conversion losses in grid import/export mode of operation. In the depicted example, the energy storage has been located with this inverter, but it could as well be located as in configurations B or C.

Combinations of the presented topologies are possible. In all cases, the microgrid side could also include other energy sources. In addition to the secured loads, sheddable loads can be placed on either the utility side or on the microgrid side in any of the configurations, but left off-line until sufficient power supply is resumed. The AC microgrid in configuration D could also be replaced by a ~650V DC distribution network.

**Island operation capability with grid synchronization**

The C50 is able to keep running when the grid goes offline. Convion has successfully completed island testing on the SOFC system. The system was able to do transitions between grid parallel and grid independent mode as planned, with a short 1s discontinuation in the power feed due to inverter reconfiguration. Research is ongoing to eliminate this discontinuation.




Ch1: yellow, UV mains voltage; Ch2: cyan, W-phase current

1: Safety switch creates the island grid
2: Mains protection recognizes the grid fault and opens grid contactors
2…3: Inverter (DC/AC) shuts down, changes operation mode to uGrid and restarts

*Figure 12: results Island mode testing of the SOFC system*

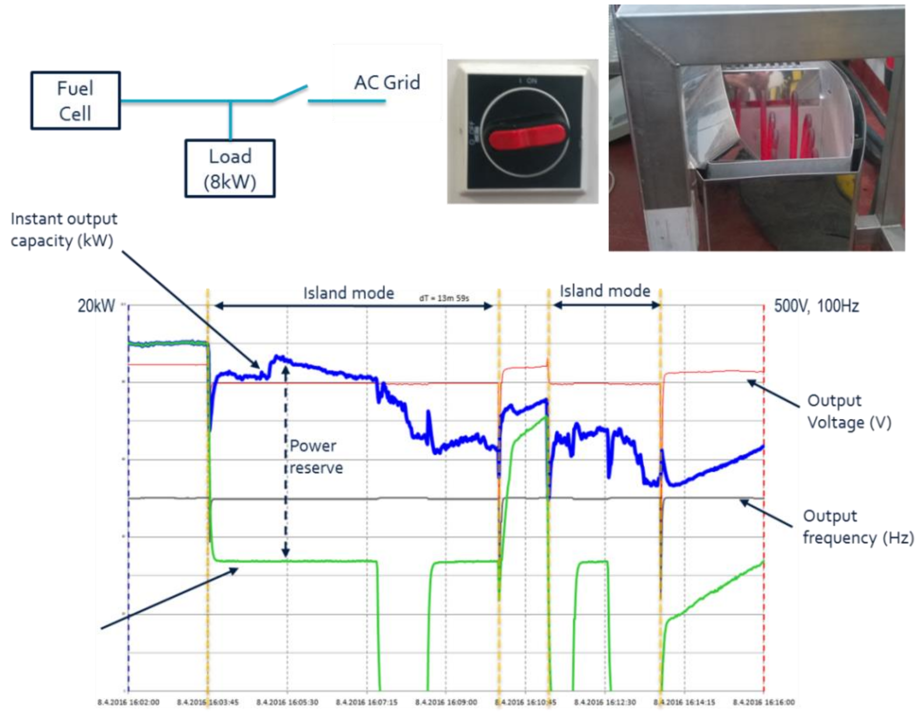



*Figure 13: island mode testing C50*

The island mode test also show that the C50 can handle subsequent load variations very well, as is depicted in Figure 11.

**Load management**

Some load variation can be handled due to the internal reforming process, which creates an internal 'energy storage'. In the grid independent mode Convion was able to respond to load variations during tests, where a load corresponding 15% of the nominal load was successfully switched on and off. System design suggests that power drops up to 50% of the nominal load can be handled. An additional battery system or load management system is needed, because of the limited ability of the SOFC to follow load. The C50 will need some load following ability, being able to ramp up or down when needed. A control system is needed where power output can be controlled by input signals from a UPS or other power management system.

### 3.5.4 Biogas feed

The C50 can handle different fuel feeds. A demonstration project at a waste water treatment plant in Italy is currently under construction. There, biogas is fed to the fuel cell after a pre-treatment. The biogas needs to cleaned of contaminants such as Sulphur and siloxanes. This can be done using a scrubber or an activated carbon filter.

The C50 is configured for a specific fuel. The provided cooling, air and fuel flow ratio are based on the type of fuel fed to the system. Is the fuel specifications are known, the parameters can be determined. Based on the parameter settings the SOFC system is fuel flexible and can be switched instantaneously without affecting the SOFC operation. This is useful for biogas application where in some cases biogas is mixed with natural gas or a fossil gas is used for back-up of the biogas. Biogas applications will likely result in a better business case when subsidies are available.

### 3.5.5 Combination with cooling

In CHP operation it is not quite uncommon to utilize a CHP in combination with an absorption chiller. In times or situations where gas is cheap or electricity infrastructure constraints occur or when electricity is relative expensive this may be economically beneficial.

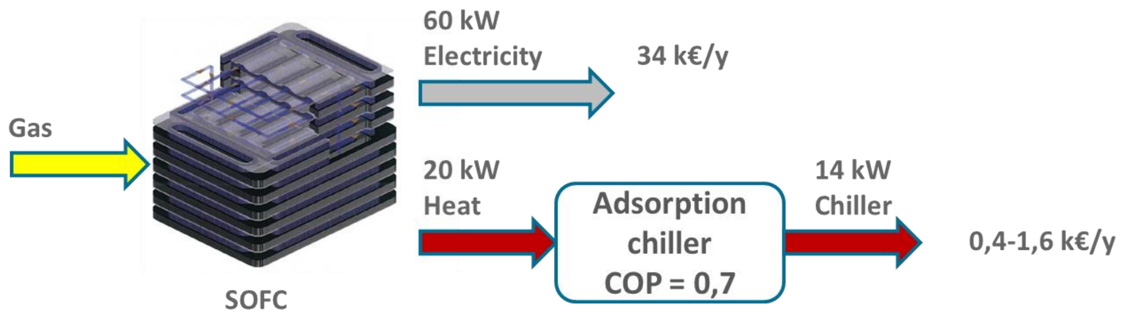



*Figure 14 – utilizing the heat of the SOFC by an absorption chiller*

However, electricity prices are relatively low and the reference system (Best Available Technology) is relatively efficient. Therefore the cooling produced has a lower value than normal heat, see also Figure 14.

### 3.5.6 Combination with desiccant dehumidification

There are several configuration options for using a desiccant wheel for dehumidification[2]. The basic principle of the dehumidification is similar for all configurations. The most basic setup is already relatively complex compared to conventional HVAC systems. A conventional HVAC system lay-out is shown in Figure 22.

The desiccant wheel is used for dehumidification in cooling mode. The desiccant wheel operates by supplying heated and therefore relatively dry return air, see Figure 15. This results in water vapor extraction for the supply air and in addition (undesired) heating. The heated air (~55°C) is firstly cooled by the heat wheel utilizing the colder return air flow. Finally the air is cooled to the desired set-point.

[2] "Technical development of rotary desiccant dehumidification and air conditioning"; D. La, et al; Elsevier, 2009

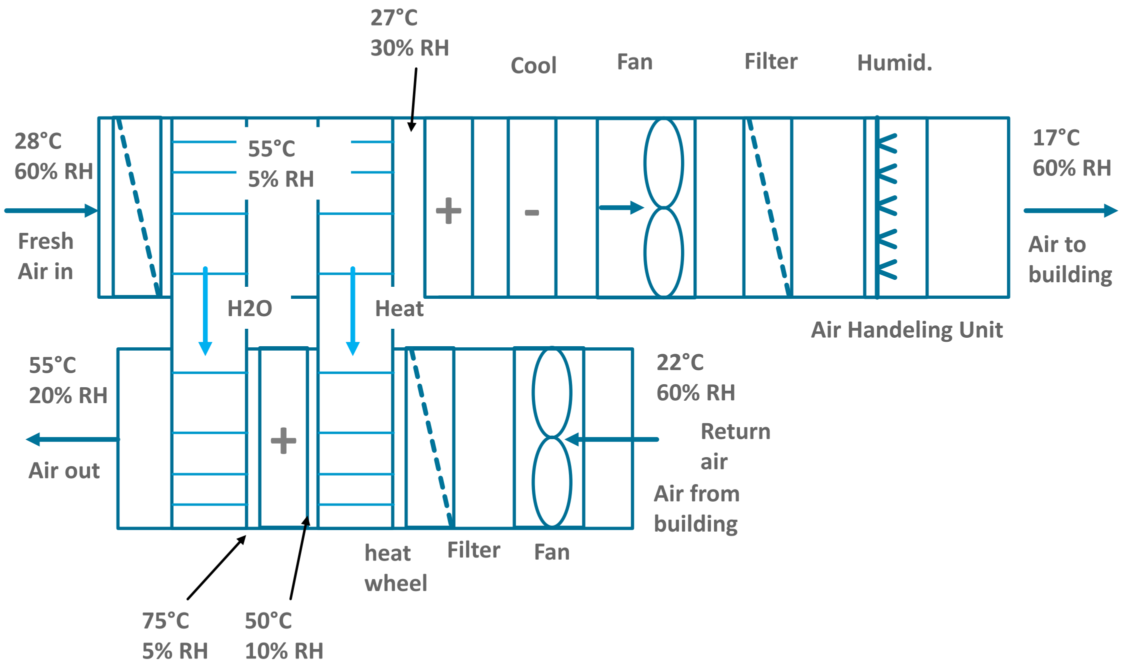



*Figure 15 – Integration of desiccant wheel in HVAC system*

The advantage is that the air does not have to be cooled to below dew-point temperatures, since it is already dehumidified by means of direct water vapor removal. The disadvantage is that the system is more complex and the air is heated, which has to be cooled again.

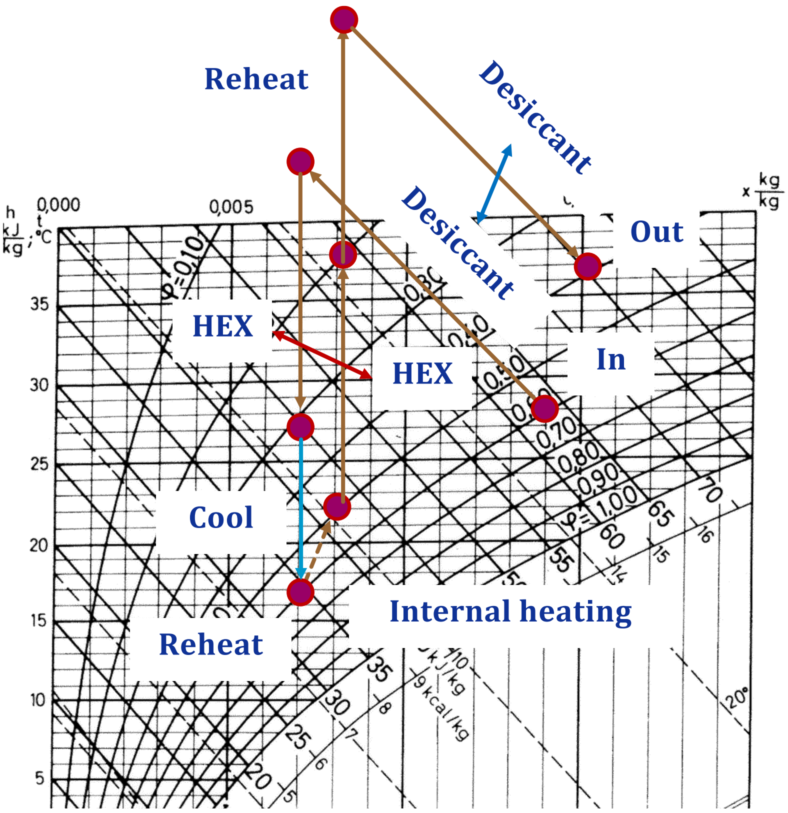



*Figure 16 – Mollier diagram of the desiccant dehumidification process.*

The desiccant humidification process is shown in the Mollier diagram which corresponds to the process conditions of system lay-out of Figure 15.

# 4 COMPETITIVE ADVANTAGES

The Convion C50 is a unique, versatile and multi-applicable system that can generate electricity and heat and a number of other services such as backup power.

In order to understand the position of the C50 we first make a comparison with other fuel cell types and after that we investigate the relative position with other technologies.

## 4.1 Fuel cell comparison

Currently, a host of distinct fuel cell technologies are available or under development. In Table 3 the characteristics of each type are shown:

| | PEM FC | AFC | PAFC | MCFC | SOFC |
|---|---|---|---|---|---|
| | | | | | |
| Net electrical efficiency AC | 40-45% | 60% | 40% | 45-50% | 60-65% |
| Quality heat | low | Low | high | high | high |
| Flexibility | high | low | moderate | low | low |
| Contaminents | NOx, S, CO2 | NOx, S, CO2 | S, CO2 | S | S |
| Fuel acceptance | Pure H2 | Pure H2 | Pure H2 | Hydrocarbons | hydrocarbons |
| Start up | fast | fast | moderate | slow | Slow |
| Lifetime | > 40k h | > 20k h | > 20k h | > 40k h | > 20k h |

*Table 4: comparison fuel cell technologies*

*Note: the net electrical efficiency is calculated based on primary fuel, for H2 fed systems this means the conversion losses of producing H2 are also taken into account.*

We see that that the SOFC stands out for high electrical efficiency and for its direct acceptance of hydrocarbons such as natural gas and the high heat quality. With these characteristics a SOFC perfectly suited for stationary applications, especially CHP applications, where no additional infrastructure or changes to the heating system are required.
However, the flexibility of an SOFC is far less than that of a PEM fuel cell. Therefore, a SOFC cannot be applied in the automotive application.

In order to understand the position of the C50 in relation to other fuel cell manufacturers we have added a list of a number of suppliers.

| Type | unit | C50 | Bloom Energy | Fuji | Nedstack | Fuel Cell Energy | Mitsubishi | Solid Power |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| technology | - | SOFC | SOFC | PAFC | PEM | DFC | SOFC | SOFC |
| Electrical power | kW | 58 | 250 | 100 | 1000 | 300 | 211 | 1,5 |
| Electrical Efficiency AC | % | 60% | 65% | 42% | 50% | 47% | 52% | 60% |
| Thermal efficiency | % | 25% | na | 49% | 30% | 43% | na | 22% |
| Size | m2/kW | 0,12 | 0,05 | 0,14 | - | 0,12 | na | 0,40 |
| Weight | kg/kW | 103 | 57 | 155 | 65 | 40 | na | 130 |
| product status | - | pre-commercial | commercial | commercial | commercial | commercial | R&D | commercial |

*Table 5: comparison C50 with other fuel cells*

The C50 stands out at its high total efficiency and specifically in this size range. FC producers such as Bloom and Nedstack aim for MW size applications whereas Solid Power aims at the residential market with their 1,5 kWe system.

## 4.2 Comparison with market alternatives

The reference system for a typical customer would be to buy electricity from the grid and make heat with a condensing boiler. But the customer has other choices in systems that have a better economic and environmental performance. The main alternatives are:

- CHP based on a gas engine
- Back-up system based on a diesel genset
- Solar PV icm batteries
- Heat pump

When compared to a gas engine CHP or a diesel genset of the same size, we see some particular advantages and disadvantages. We start to describe the strengths of the system compared to other products:

| Strengths: | |
|---|---|
| | |
| High electrical efficiency | Compared to a gas engine of the same size the C50 has more than 50% more electrical output. This is especially advantageous in situations where electricity has a high value, such as biogas produced electricity |
| Back-up power capability | The C50 combines the function of a CHP with that of a diesel generator and a UPS |
| Hot switch capability | Biogas producers that have a unused portion of biogas might be able to monetize this stream by using it together with natural gas |
| Nearly zero emissions | Near zero emissions of NOx, CxHy and fine particles make the system suited for areas with NOx limitations like London and possibly also for utilizing the CO2 for greenhouses. |
| Low frequency maintenance | Maintenance is only needed once a year. This makes it interesting for more remote locations |
| Decentralized DC power | Some end-users are experimenting with the use of DC power to cut off excess power electronics and reduce power consumption. Continuous |

*Table 6: Competitive strengths*

Due to the above mentioned strengths the C50 can be used in specific market niches where they have higher added value. One can think of a data center where there is a need for back-up power, low emissions and DC power.

The C50 also has some weaknesses at this moment:

| Weaknesses | |
|---|---|
| | |
| Size | Despite the high energy density of the C50 the unit is a factor 2-3 bigger than a gas engine CHP |
| Weight | Despite the high energy density of the C50 the unit is a factor 2-3 heavier than a gas engine CHP. At its current weight the C50 might not be applicable for roof mounted applications in all sites |
| Gas Pressure | 4 bar gas pressure may require the use of an external gas compressor. A 4 bar gas connection is common in industry applications, but not in utility buildings or horticulture. Small clients might benefit a lot from a 50 kW fuel cell but lack the gas connection, while large clients that have a suitable gas connection might pay too little for energy to make the case work. |
| | Some large digesters can provide biogas at 4 bar pressure. |

*Table 7: Weaknesses of the SOFC system*

## 4.3 Environmental performance

The C50 has a very high efficiency which in turn gives it a good position as an environmental friendly application. We have therefore made a comparison between a reference situation (condensing boiler and electricity grid) , a ground source heat pump, the C50 system and a combination of both.

Since the outcome is very dependent on the local emission factor of the grid and the amount of heat that can be delivered by the fuel cell, we have distinguished two users and two emissions factors. For the users we simulate a peak user where the fuel cell provides 30% of the heat, where the rest of the heat is delivered by a boiler and a baseload user where 60% of the heat is provided by the fuel cell.

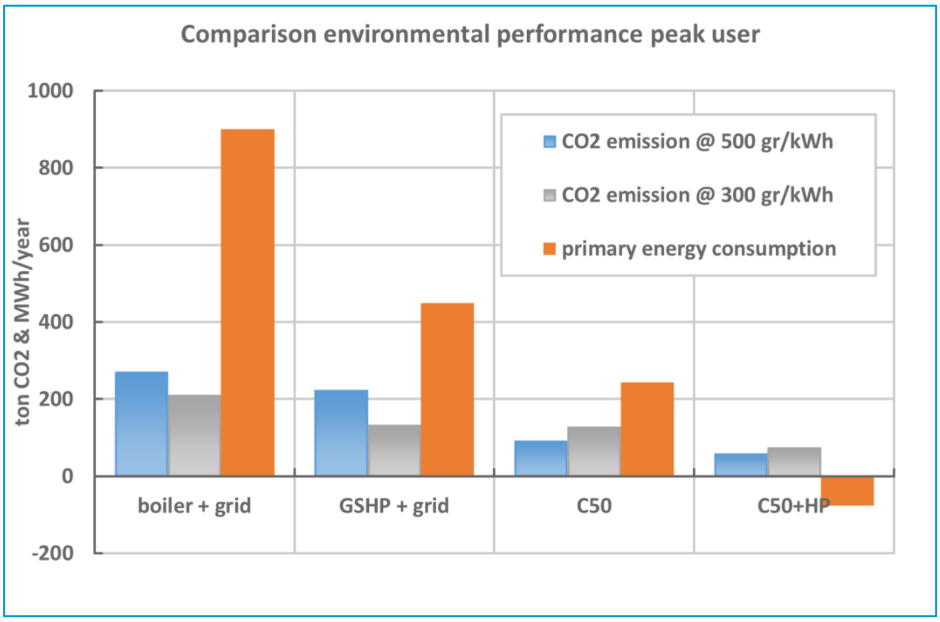



*Figure 17: Comparison environmental performance peak user*

For the peak user, we can clearly see that the primary energy consumption of the fuel cell is much better than the reference situation and that of a heat pump. The combination of the two systems is the best option. For this user, this even results in a negative primary energy consumption.

For the baseload user, we see the same results, only the amount of electricity produced is fairly large in relation to the consumption which leads to both negative emissions and primary energy consumption.

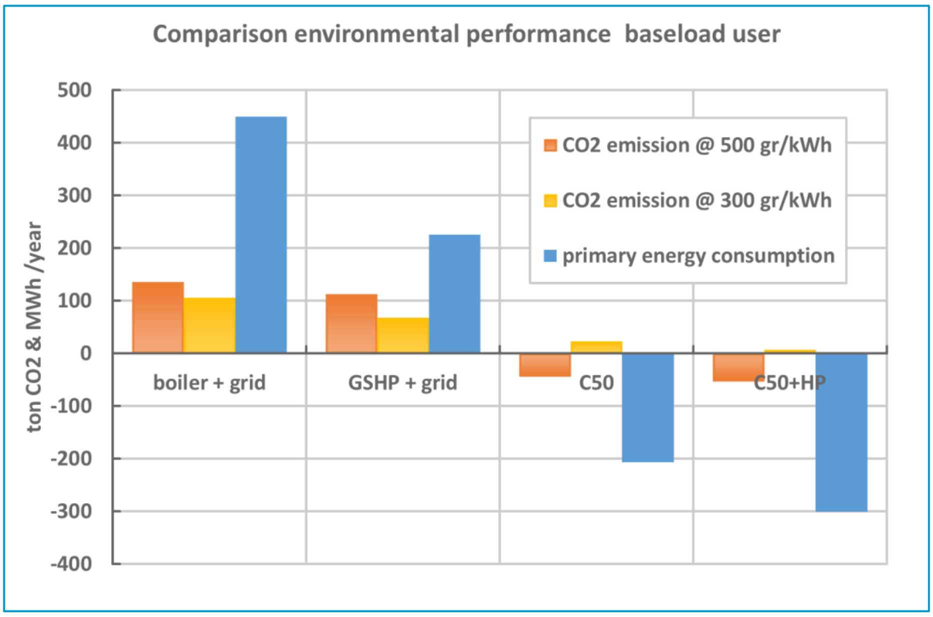



*Figure 18: comparison environmental performance baseload user*

**NOx emissions**

European regulations concerning emissions (NOx, but also particulate matter and Sulphur dioxide) are becoming increasingly more stringent due to building scientific evidence of adverse health effects. Gas engines require tuning and in some cases selective catalytic reduction and filters to meet the standards.

However, these standards are still above safe concentrations as indicated by the WHO. In the Netherlands for example, the background concentration is 40 µg/m3 (which is also the safe limit), from which less than 25% is biogenic. Small gas engines are allowed to emit 340 µg/m3[3] which is more than 8 times the safe limit. Most gas engines still operate at 500 µg/m3 or worse.

[3] Infomil, 2016. The Netherlands. Emissiegrenswaarden voor kleine en middelgrote stookinstallaties

# 5 APPLICATIONS

There are many possible applications for the C50 fuel cell. This chapter contains a description of user groups and typical applications. A long list of possible applications can be found in the Appendix: Long list of applications.

The C50 can operate in power only mode and in CHP mode. We therefore distinguish the following main user segments:

- (smart grid) CHP
- Renewable CHP (biogas with subsidy regimes EU)
- Prime power (power only applications)
- Maritime power

These segments will now be described in more detail. We focus on applications where a 60 kWe or multiple of these baseload fuel cells would fit.

## 5.1 Smart grid CHP

The high efficiency fuel cell is an excellent choice for providing decentral heat and electricity to consumers. The low emissions, high efficiency and high reliability make it a great system for the built environment and for horticulture. This user group will run the C50 on natural gas in CHP mode. Biogas is likely less available for this user group, but when available this can improve the case even more. The C50 can be operated in a local (smart) grid or can provide energy directly to a building or greenhouse.

Several applications can be distinguished:

**CHP in local smart grid with district heating**

- The flexibility and/or prime power function that the C50 provides can be utilized by (local) energy companies in their production portfolio to optimize their
- Heat can be delivered to district heating network or to local buildings
- This may also provide an interesting financing opportunity due to abilities of (public) energy companies

**CHP in buildings with backup power**

- Prime power, i.e. for server rooms, digital locks etc. Can be used for mission critical applications (i.e. server rooms, with an UPS) or non-critical loads (security systems, HVAC, lighting, elevators)
- New buildings: integrate in boiler room or place outdoor
- Renovation: not likely (a separate boiler room would need to be built outside of the building.
- In multi-tenant buildings, the power can directly be delivered and sold to the end-user, the so-called “behind the meter concept”. This makes the business case significantly more attractive.

**Horticulture with CO2**

- Intensive horticulture (with lighting) or extensive horticulture possible
- SOFC to power auxiliary systems, i.e. pumps
- Due to size and weight system likely installed outside
- DC power can provide significant savings

**Energy efficient buildings**

- Heat and power delivered within building
- Efficient decentral electricity production decreases the electricity import, which is very beneficial in improving energy labels.
- The SOFC is cheaper than solar on the basis of €/ton CO2 avoided. However: the energy is only renewable when biogas is used. NZEB require a share of renewable energy, so an SOFC on natural gas will not make solar obsolete.

### 5.1.1 Typical Heat profiles

One important factor that influences the profitability of a smart grid CHP is the potential heat utilization. To get an idea of how a CHP application works we show an example of a typical swimming pool which is an excellent CHP application due to the continuous high temperature heat demand.

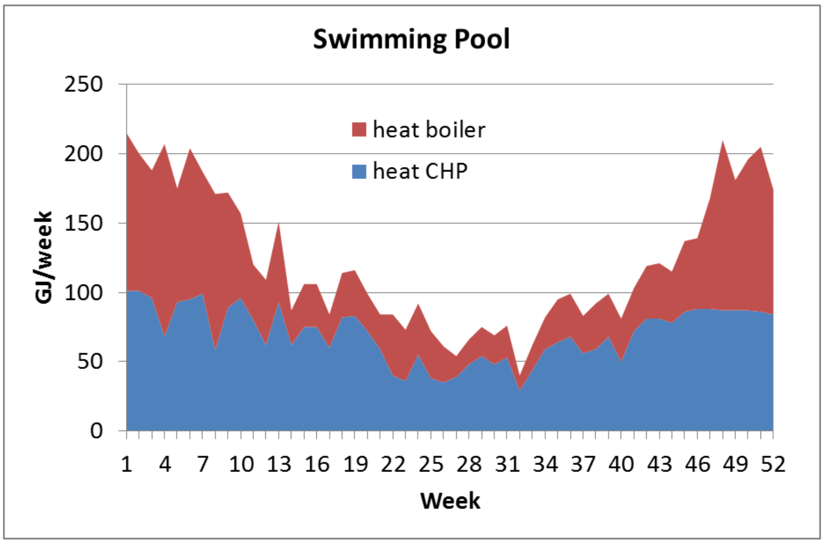



*Figure 19: heat profile swimming pool with CHP*

We can see that the CHP meets the baseload demand of heat and the boiler covers the peak.

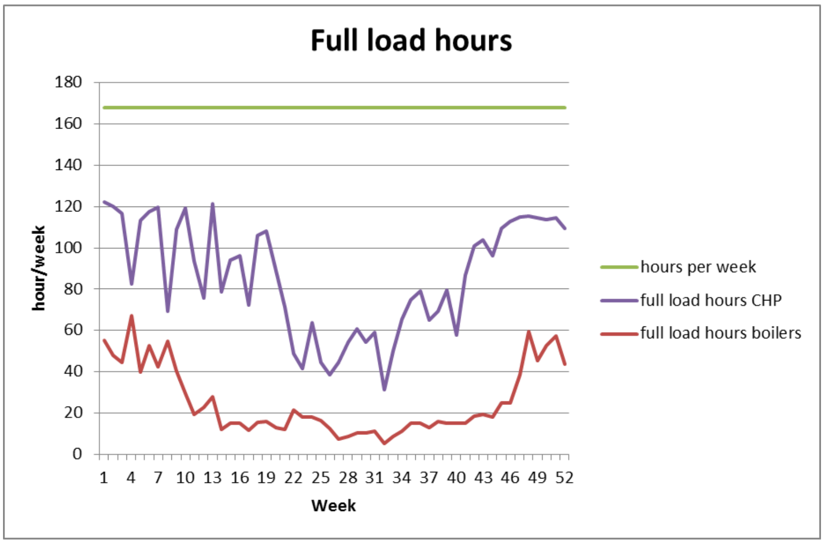



*Figure 20: load hours CHP swimming pool*

For the full load hours we can see that the gas engine CHP is operated mostly during peak hours to produce the most valuable electricity.

Heat utilization will differ for the various types of applications, such as a normal office, laboratory, hotel, etc. To get to a better understanding of different heat profiles we have listed the amount of full load hours per application in Table 8.

| Type | Heating capacity | Parameters | Full load hours |
|---|---|---|---|
| - | kW | - | h/y |
| Swimming pool | 1100 | gFA = 5 000 m$^2$ | 6000 |
| Office building | 600 | gFA = 9 000 m$^2$ | 6000 |
| Lab building | 2400 | gFA = 25 000 m$^2$ | 7500 |
| Lab building with absorption cooling | 5000 | gFA = 50 000 m$^2$ | 7700 |
| Air handling unit laboratory (twin coil) | 180 | Volume flow 30 000 m$^3$/h | 8760 |
| Air handling unit laboratory (re-circulation) | 60 | Volume flow 24 000 m$^3$/h | 8760 |
| Air handling unit office without humidity control (cross flow) | 190 | Volume flow 48 000 m$^3$/h | 6300 |
| Air handling unit heat wheel | 30 | Volume flow 23 000 m$^3$/h | 1000 |
| Hotel (medium) | 400 | gFA = 5 000 m$^2$ | ~ 7000 |
| Hotel (large) | 1400 | gFA = 20 000 m$^2$ | ~ 7000 |
| Industry | 6700 | 10 bar steam | 8300 |

*Table 8 – Heat utilization for different types of applications*

The heat utilization can be expressed as the hours of useful SOFC heat production or base load hours. The visualization of determining base load hours for the situation of air handling unit laboratory (twin coil) is shown in Figure 21.

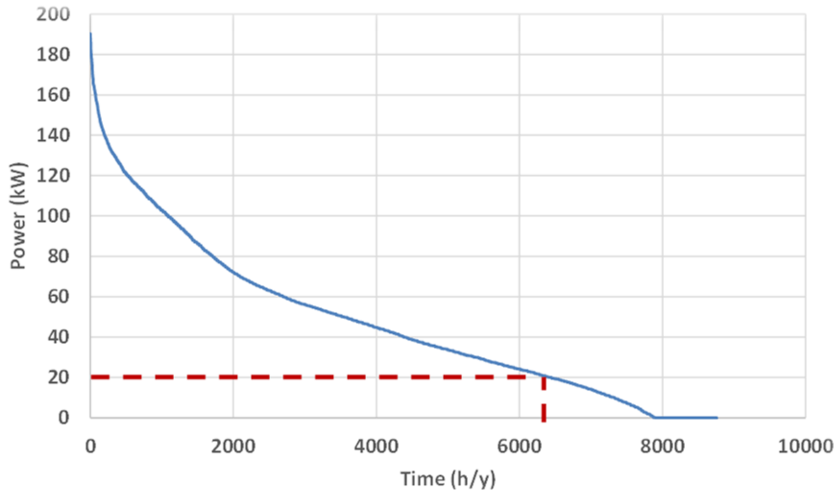



*Figure 21 – Heating load for a 48 000 m3/h capacity air handling units for office type building utilizing cross flow heat ex-changer for heat recuperation. There is no re-heating since no humidity control is present during the summer.*

The most promising applications are buildings which utilize a hot water circuit which should be kept warm constantly due to avoid the growth of the Legionella bacteria. The water temperature should be around 60°C, so a supply and retour temperature of 80/65°C would be necessary. This is no problem for the SOFC, but for heat pump systems this is a challenge and results in overall efficiency loss of the heat pump system.

Other advantageous applications are air handling units which use humidity control during the summer. For these systems re-heating is utilized during cooling, in this case the air is cooled to required dew-point (8°C) and reheated to minimum air temperature (15°C). A lower temperature than 15°C results in a too cold supply temperature for comfort; cold neck.

Industry and HVAC units with a heat wheel are less advantageous. The industry application typically has constant heat use, so a lot of effective operational hours. However, in most European counties the energy prices are relatively low compared to small and medium size energy users.

The HVAC with an heat wheel has very low energy use and low amount of operational hours. Modern office building typically use a heat wheel. For laboratory purposes this is not allowed due to bio contamination or other hazardous materials in the return air.

The various heat profiles are added to the model that analyses the use cases.

### 5.1.2 System design with HVAC system including reheating

The C50 can provide hot water for space heating and hot water. But even a user that supplies their cooling with a conventional HVAC system requires heat in the summer. We will investigate this application in further detail. A schematic overview of a HVAC can be seen in Figure 22.

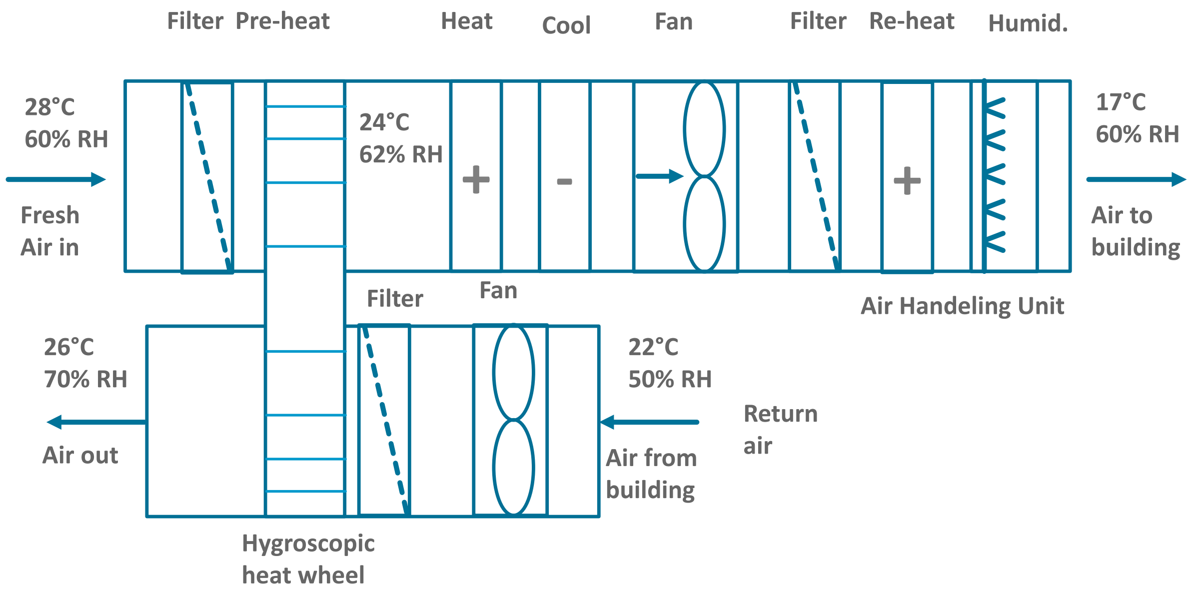



*Figure 22 – Conventional HVAC lay-out (Best Available Technology) for normal office application. RH stands for relative humidity.*

The supply air duct consists of a coarse filter, heat wheel, heating coil, cooling coil, fan, fine filter, reheating coil and humidifier. The return air duct consists of a fan, exhaust filter and again the heat wheel. There are two basic operating principles: winter and summer conditions, or heating and cooling mode.

**Heating operation**

Room conditions during a cold winter day are typically 20°C and 30% relative humidity. The relative hot air is cooled down in the heat wheel to approximately -5°C depending on the heat wheel efficiency. This heat is added to the air intake duct increasing the temperature from -10°C to 10-15°C depending on the amount of return air flow compared to the supply air flow. Similarly, the relatively high concentration of water vapor of the return air is transported to the intake duct by the hygroscopic (water absorbing) material, increasing the inlet humidity. After preheating by the heat wheel, the air is heated to the desired inlet temperature or higher if adiabatic humidification is used. Finally, the air is humidified to the required relative humidity of 30% or higher.

**Cooling operation**

For the cooling process, the air inlet is cooled by the heat wheel and cooled further by the cooling coil. By cooling below the dew-point at (in the depicted example at 18°C), the air is dehumidified and cooled to 8-10°C to achieve the required relative humidity of approximately 60%. This air is too cold for supply and is reheated to 15°C or higher, otherwise this will lead to complaints with regard to a too cold air flow.

**Re-heat**

The aforementioned re-heating of the air during cooling mode results in a need for heat supply during winter and summer. By utilizing the SOFC heat (as Combined Heat and Power) for Heating Ventilation Air-conditioning Cooling (HVAC) purposes the amount of so called "full load hours" are relatively high. I.e. a lot of heat is put to good use.

**Full load hours of lab HVAC**

The HVAC equipment for office type buildings are less intensively used as the HVAC equipment for cleanrooms and laboratory environments (universities, hospitals, pharmaceutical companies, etc.). Based on the measured energy use from a lab building, the following load-duration curve has been derived for the dehumidification.

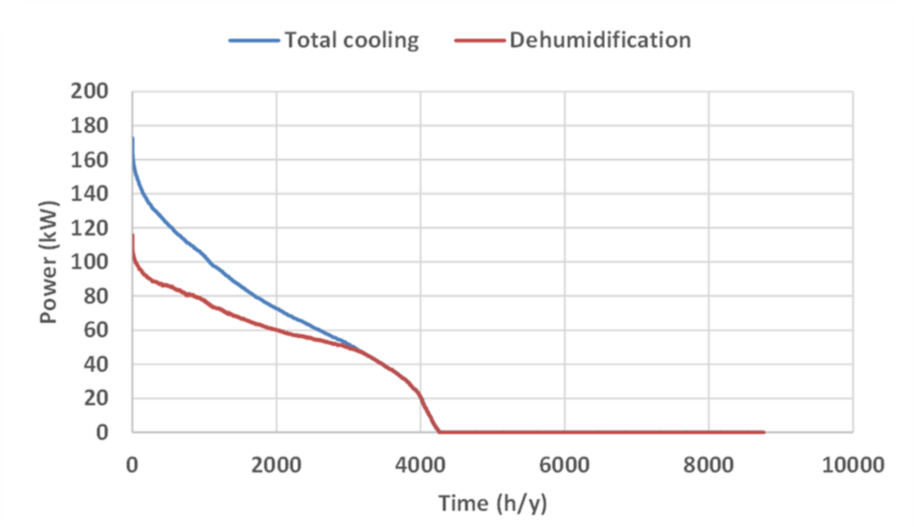



*Figure 23 – Load duration curve for dehumidification versus total cooling load based on measured energy use of a lab building*

The total full load hours including the re-heat during the summer and heat use during the winter are determined at 7000 hours per year. This is more than for a normal office, for which the full load hours are 4600 hours per year.

## 5.2 Renewable CHP

A substantial number of biogas producers is already active in Europe, where organizations such as wastewater treatment plants, food processing companies, breweries use anaerobic digestion to produce biogas. And given the low penetration of anaerobic digestion, the addressable market could grow substantially the coming years. For example, currently 4 TWh of electricity are produced annually from European wastewater treatment plants of which there are almost 10,000 in Germany, more than 8,000 in the UK, 7,600 in Italy and 3,000 in Poland.

This user group will run the C50 on biogas in CHP mode. In several countries, for example Italy, this can provide large benefits. The C50 requires a minimum methane fraction of 60% and can perform a 'hot switch' between natural gas and biogas, provided that some transition time with downregulation is taken into account.

A compressor might therefore be needed as there are few locations where biogas or upgraded biogas is available at 4 barg or higher (in The Netherlands ~10 locations). Examples mainly include waste incinerators and the sugar industry.

**Waste water treatment plant**

- Biogas needs to be cleaned thoroughly
- Good fit in baseload heating demand for digester
- Abundant throughout EU

**(Mono)manure digesters**

- Technology is becoming more widespread – big market potential
- Most suitable in power rating
- Good fit in baseload heating demand for digester

**Breweries**

- Abundant throughout EU
- Applications especially for micro-breweries

**Dual fuel operation biogas/natural gas, for example digesters**

- Hot switch possible
- For digesters with excess biogas, mixing with natural gas when needed.
- Farms are not well suited for pure biogas operation: heat demand is low and biogas production is only sufficient on very large cattle farms. Biogas can be mixed with natural gas.

**Specialty gasses, landfill etc.**

- Probably no heat use
- Not suited in general due to low methane content.
- Probably not suited for 60 kWe baseload fuel cells.

## 5.3 Prime power

This user group will run the SOFC on power only mode, providing reliable and clean power. The SOFC provides a clean and reliable alternative to diesel generators. It is capable of handling small load variations due to a smart system where energy can be 'stored' in the gas reformation. Direct current power delivery is not yet common, but of increasing interest. The SOFC can provide this and therefore limit conversion losses that occur in IT-infrastructure. More information on prime power architectures see Paragraph 3.5.3.

The C50 is designed to run fulltime, and will therefore likely be used for continuous power (constant load) or prime power (varying load). Some load variation can be handled due to the internal reforming process, which creates an internal 'energy storage'.

The SOFC can modulate between 50% and 100% of nominal power. If large power demand fluctuations are present, then a small auxiliary battery should be applied. The inverter has been configured in a way that grid connection and disconnection can happen without discontinuation. Local data centers and server rooms form an interesting target group. Improved redundancy can be achieved, from "N+1" to two independent power feeds "2N". This yields value, especially for server rooms. Fuel cell systems powering data centers have been installed in the US by Bloom Energy. A study on Facebook's servers shows that power fluctuations on server rack level are limited, and the aggregate power fluctuations at the main switch board are almost negligible (see Figure)

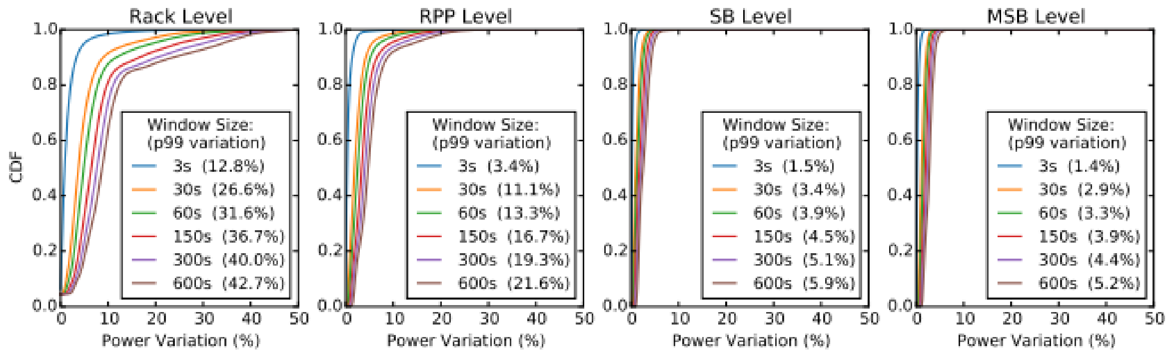



*Figure 24: The measured power variations over different time windows for power devices at rack and switchboard level. source: systems infrastructure[4].*

The C50 fuel cell working parallel with the grid provides reliable power, up to 20 times higher than grid power alone. The unavailability of the SOFC due to scheduled and reactive maintenance is independent of the state of the power grid. When using multiple units in a grid-parallel configuration, the reliability increases even further.

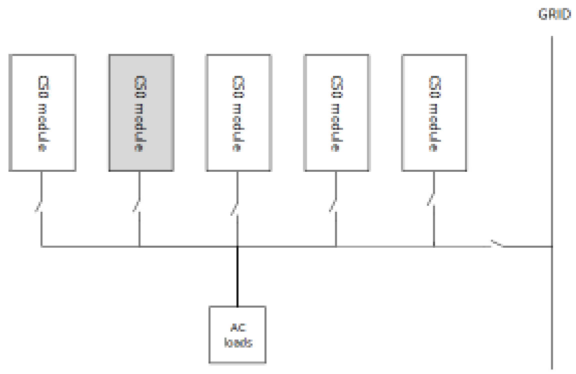



*Figure 25: grid parallel N+1 configuration*

**Micro servers/small data centers**

- Many large companies, universities, banks and IT companies have their own server rooms
- Large data centers are multi-megawatt scale and too large for this system
- Electricity can be relatively cheap for these customers
- No heat use
- Reliable 24x7 prime power generation

[4] Wu & Deng, 2016. Dynamo: Facebook's Data Center-Wide Power Management System.

**Remote locations, i.e. micro grids, farms etc.**

- No heat use
- SOFC not suited for farms and telecom based on rated power (too high) and lack of suitable gas infrastructure.

## 5.4 Maritime

The Shipping sector is increasingly looking for ways to limit emissions. LNG shipping for short shipping applications is becoming more common, as an alternative to polluting diesel and heavy fuel oil. Having a generator on board with a high electrical efficiency and near zero emissions can be of great value. This user group will run the SOFC in power only mode on a ship to provide auxiliary power. The SOFC is capable of handling load variations as described above.

In ports, ships use auxiliary power engines for electricity production. When at sea, these engines are switched off. Instead, power take-off (PTO) from the main engines is used since the fuel of the main engine (HVO) is cheaper than the auxiliary power unit (MDO). Producing auxiliary power on a ship is relatively expensive.

However, the size and weight of the fuel cell in current conditions will make it hard to compete with diesel generators. The SOFC will have to be modified to run on LPG/LNG/CNG and vibrations will need to be considered. This user group is therefore not seen as 'launching customer'.

| Comparison with existing technology | Marine diesel auxiliary genset | SOFC |
|---|---|---|
| | | |
| Power kW | 85 | 60 |
| Size (length/width/height) in m | 1.0 x 0.75 x 0.9 | 2.6 x 2.0 x 2x3 |
| Weight (kg) | 600 | 4000 |

*Table 9: Comparison SOFC with marine diesel genset*

## 5.5 User requirements

This chapter contains a description of user requirements of a fuel cell system and how this suits the C50.

**High electrical efficiency**

A high electrical efficiency is required by certain user groups, for example horticulture. Electricity is the most important value driver, and efficiency must much be higher than competing technologies (i.e. gas engines have typical electrical efficiencies of 35-40%) to make up for higher investment cost.

**Heat and thermal efficiency.**

Low temperature heat from the cooling circuit of the fuel cell max 20-25 kW, can be used. The heat efficiency is only important in CHP applications, where it also has an impact on the energy label of buildings.

**Availability, reliability, continuous power and prime power**

One of the key advantages of the C50 is that it can run fulltime. For continuous and prime power applications, it is important that the running hours are high, the scheduled downtime is low and that the risk of shutdown outside of maintenance is low. Maintenance intervals are important to consider at remote locations. For mission critical applications, it is important to make sure the transition to grid and island mode is seamless.

**Useful CO2 – purity and CO levels**

The exhaust gas can directly be blown into the greenhouse. The carbon monoxide CO emission level of the C50 is below 20 ppm. This is below the maximum acceptable concentration (MAC) level of 25 ppm in the Netherlands. However, WHO and EU regulations prescribe an 8 hour average concentration of maximum 8.1 ppm carbon monoxide.

**Fuel flexibility and subsidies**

The biogas application seems very interesting, due to cheap feedstock and high subsidies in several countries. The size of the C50 matches well with that of mono-digesters of manure which are expected to become a large source of energy.

The fuel flexibility might also open opportunities for biogas producers that have a seasonal or batch process influence, where excess biogas has to be flared. This can sometimes be 20-30% of total biogas production. In such cases the C50 can “hot”-switch between biogas and natural gas if a natural gas supply is available. The C50 is capable of switching fuel, if the fuel characteristics are known. If the fuel cell runs partially on natural gas, only the biogas part will be subsidized.

**Size, weight and noise**

When placing the SOFC in buildings, the weight, noise and size will be of concern. We assume the fuel cell will be installed at ground level. Due to its size, it’s unlikely to be installed in boiler rooms not on ground level. The C50 is heavy, this could be an issue for some clients. Outdoor application has some advantages, see Paragraph 3.3.

**Size match: 60 kWe fuel cell**

A client must have a high enough energy consumption to justify a 60 kWe baseload generator. However, if the client has a very large energy demand, the price he pays will be low so the fuel cell will generate less value. Because the fuel cell will need to be connected to a high pressure gas grid (4 barg or higher), an industrial gas connection is needed.  The mismatch between the required industrial gas connection and the preference of a smaller consumer (due to higher electricity value) provides a challenge.

| | (smart grid) CHP | | | | Bio-CHP | | | Prime power | | Maritime power |
|---|---|---|---|---|---|---|---|---|---|---|
| **Priority** | **horticulture incl. CO2** | **buildings CHP with backup power** | **flex CHP local power station** | **Near zero energy building CHP with DC power** | **pure biogas/ syngas baseload** | **dual fuel bio/NG** | **specialty gasses, i.e. landfill** | **Contineous power i.e. server rooms** | **remote locations & backup power** | **Shipping** |
| High electrical efficiency | ++ | + | + | ++ | ++ | ++ | ++ | + | + | + |
| Thermal efficiency | ++ | + | + | ++ | + | + | + | 0 | 0 | + |
| Availability | + | ++ | 0 | + | 0 | 0 | 0 | ++ | ++ | + |
| Reliability | + | ++ | + | + | 0 | 0 | 0 | ++ | ++ | + |
| CO2 purity | ++ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Noise level 70 dBA | 0 | 0 | 0 | 0 | + | + | + | 0 | + | + |
| Size | + | 0 | + | 0 | + | + | + | 0 | + | - |
| Weight | + | 0 | + | 0 | + | + | + | 0 | + | - |
| Few start/stop per year | + | + | - | + | + | + | + | + | - | + |
| Minimum methane content >60% | + | + | + | + | + | + | -- | + | + | + |
| Value hot-switching gas input | 0 | 0 | 0 | 0 | 0 | ++ | 0 | 0 | 0 | 0 |
| 60 kWe size suitable | + | + | + | + | + | + | + | + | -- | 0 |
| | | | | | | | | | | |
| Suitable? | yes | yes | maybe | yes | yes | yes | no | yes | no | no |

*Table 10: user requirements fuel cell applications*

| **Legend** | |
|---|---|
| Excellent fit | ++ |
| Good fit | + |
| Possible fit | 0 |
| Limited fit | - |
| Critical | -- |

**Smart grid CHP applications**

Smart grid CHP applications run on natural gas and have a useful application for heat. High electrical efficiency and reliability are important value drivers. Size and weight require outdoor installation in most cases. A gas compressor might be needed due to limited availability of high pressure gas connections. The example cases horticulture, buildings (with backup power) and new energy efficient buildings seem a good fit for a fuel cell system.

Application in a decentral power station requires great flexibility and on-off switching, however the fuel cell might be able to provide baseload decentral power and some ramp-down capacity to city districts, supplemented by the grid or by other generators.

**Bio-CHP applications**

Bio-CHP applications run directly on biogas, or in dual fuel mode. Because biogas is available in more remote locations, the requirements for size and noise are of less importance. The high electricity output and low heat output corresponds well with the local need for need in the digester and the possibilities to export excess electricity to the grid, which can be problematic for gas in the summertime. The size of the C50 matches well with that of mono-digesters of manure which are expected to become a large source of energy.

Reliability is a bonus, but not as critical as application in buildings and horticulture. The possibility of running on biogas, natural gas or a mix is an advantage to other generators. The fuel cell is capable of switching fuels during operation. Specialty gasses like landfill gasses that are of low methane content are not suitable at this moment.

**Prime power**

Prime power applications depend on the reliable, continuous power that the C50 can provide. Server rooms seem suitable applicants, due to the replacement of diesel generators and UPS systems. The grid functions as backup/peak provider. Remote locations seem less suited, because the fuel cell is not suited to completely replace diesel generators in this situation. This is due to the lack of connection to the gas and electricity grid.

**Maritime**

An LNG/LPG fuel cell can provide auxiliary power to ships. The size, weight and vibration sensitivity will likely make the fuel cell less suitable compared to existing technology.

# 6 ECONOMIC EVALUATION

## 6.1 Main economic assumptions

### 6.1.1 Energy prices

Energy prices vary greatly throughout Europe and throughout time. Figure 26 shows how the electricity rates in Europe vary greatly between countries. Countries in North-West Europe pay the highest rates, while Eastern Europe and Scandinavian countries pay a much lower rate.

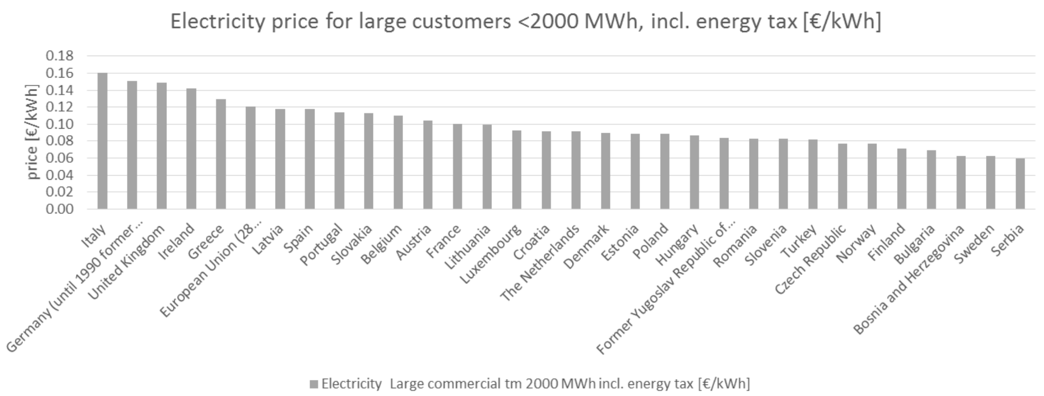



*Figure 26: Electricity rates in Europe for large customers. Source: Eurostat 2016*

The spark spread is often used to indicate the market conditions for CHP systems and states the difference between the market price of electricity and its cost of production. Figure 26 shows the spark spread, but based on electricity and gas prices including energy taxes. Some countries, for example Italy and the Netherlands, have tax exemptions for electricity and/or gas consumed by CHP systems.

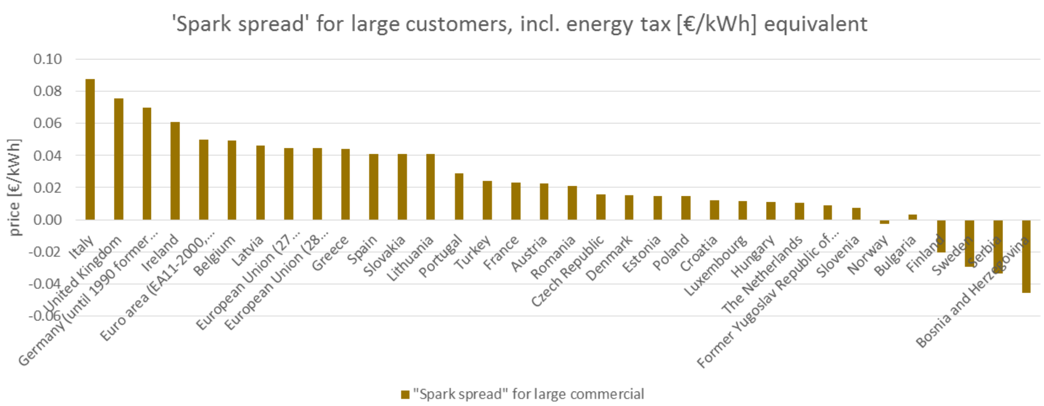



*Figure 27: 'Spark spread' in Europe for large customers. Source: Eurostat 2016*

*The energy rates also depend on the energy consumption of the customer. Each country has different thresholds for taxes. The Eurostat classification is used in this report, creating three customer types based on energy demand (see*

| Customer type | Electricity | Gas |
|---|---|---|
| | | |
| Small commercial | <500 MWh/year | <300.000 m3/year |
| Large commercial | 500 - 2000 MWh/year | 300.000 - 3.000.000 m3/year |
| Industrial | >2000 MWh/year | >3.000.000 m3/year |

Table 11). The C50 will likely be placed in small commercial or large commercial applications. Industrial customers will prefer larger systems, and their low energy prices make the C50 not a good fit (unless biogas subsidy can be acquired).

| Customer type | Electricity | Gas |
|---|---|---|
| | | |
| Small commercial | <500 MWh/year | <300.000 m3/year |
| Large commercial | 500 - 2000 MWh/year | 300.000 - 3.000.000 m3/year |
| Industrial | >2000 MWh/year | >3.000.000 m3/year |

*Table 11: Customer types based on energy demand*

### 6.1.2 Spark spread

The spark spread[5] is unfavorable for CHP systems[6] that feed their production directly to the grid. Producing electricity for self-consumption however is still viable in most countries. The difference between the gas and electricity price (including taxes) is the most favorable in the UK, Germany, Italy, Ireland, and Belgium (see Figure 28).

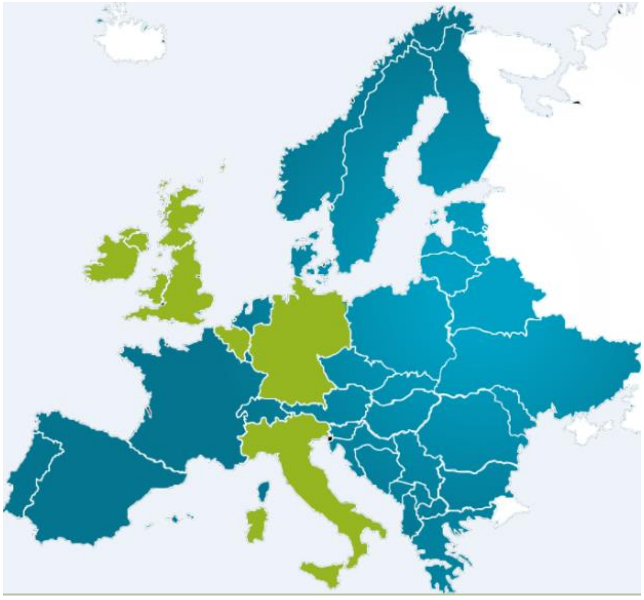


*Figure 28: Favorable gas and electricity prices for CHP systems. Source: Eurostat 2016.*

### 6.1.3 Renewable subsidies

The subsidy schemes for biogas produced electricity are presented in **Error! Reference source not found.**. It is clear, that in some countries, for example Greece and Italy, the value of biogas produced electricity is much higher than the commodity price. These countries could function as 'launching customers'. Figure 30 shows the county map with biogas subsidies, where green indicates biogas subsidies.

---

[5] The spark spread is the difference between the price received by a generator for electricity produced and the cost of the natural gas needed to produce that electricity

[6] COGEN EUROPE, 2015. CODE 2 project. http://www.code2-project.eu/wp-content/uploads/CODE-2-European-Cogeneration-Roadmap.pdf

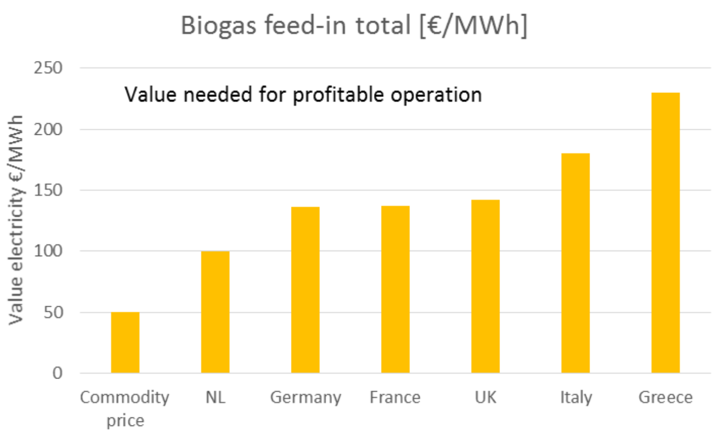



*Figure 29: Biogas produced electricity value. Source: RES Legal EU[7], 2016*

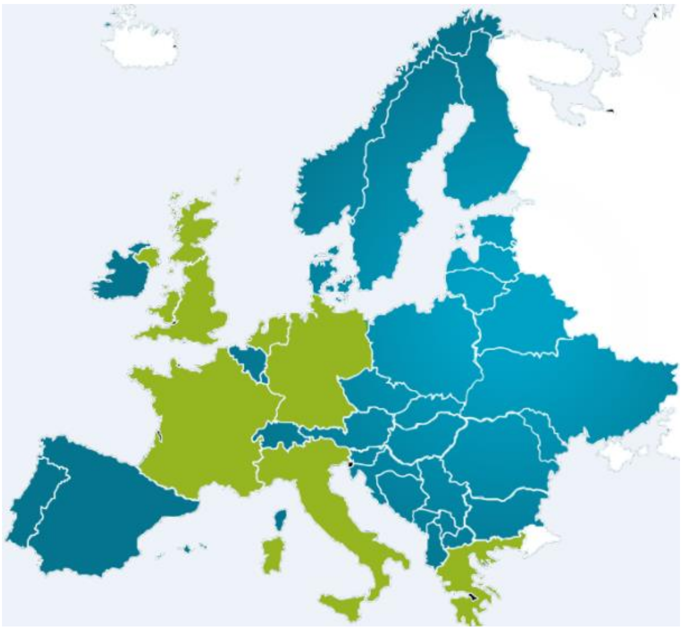


*Figure 30: Biogas subsidies in Europe. Source: Eurostat 2016.*

### 6.1.4 CHP subsidies

A great number of European countries have some sort of incentive for CHP in place. These can either be fiscal, tax exemptions, capital subsidies, operational subsidies or certificate systems.

The CODE2 project has supplied an overview of measures across the EU:

[7] http://www.res-legal.eu/

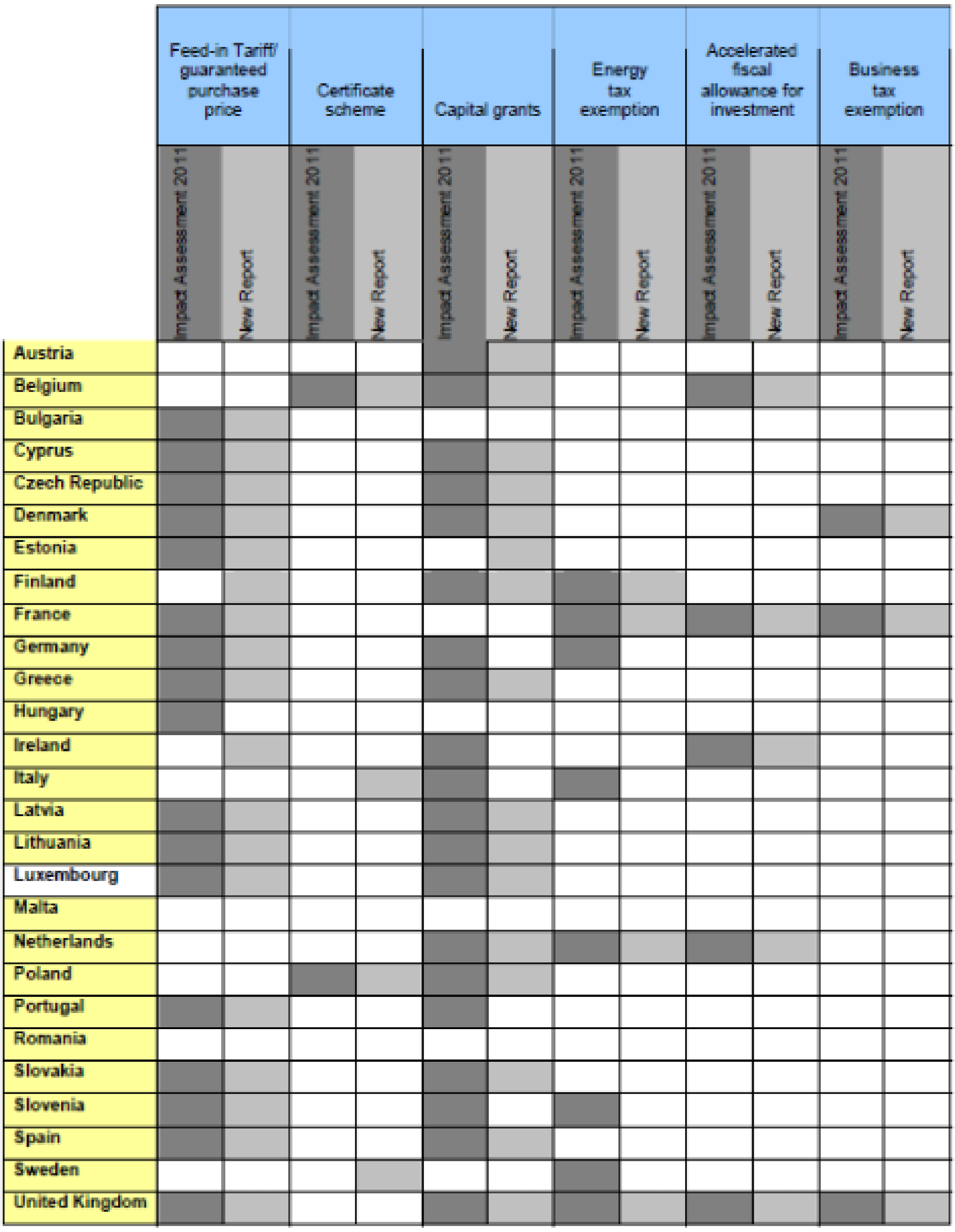



*Figure 31: Overview of EU support measures for CHP (source CODE2 project)*

It has to be noted that incentives for CHP in the past have been very ambiguous, they can appear or disappear very fast as a consequence of policy changes.

### 6.1.5 Prime power

A study by the Aberdeen Group estimated that companies lose an average of $138,000 for every hour their data center is offline. For a bank this can be $6 million per hour. In hospitals it is used to power the operating room and HVAC. Ergo: clients want to pay for reliability.

Especially data centers are increasingly focusing on redundancy. Server rooms and datacenters are classified using the TIER methodology.

- Tier 1 = Non-redundant capacity components (single uplink and servers).
- Tier 2 = Redundant capacity some components.
- Tier 3 = N+1 redundancy with backup power and multiple uplinks.
- Tier 4 = 2N+1 all components are fully fault-tolerant including uplinks, storage, chillers, HVAC systems, servers etc. Everything is dual-powered.

Tier 4 data center considered as most robust and less prone to failures. Tier 4 is designed to host mission critical servers and computer systems. Very few datacenters achieve Tier4. Tier 4 is hard to achieve, because a second power supply is needed that is capable of running full load for extended amounts of time. A diesel genset is not suitable for this but the INNO SOFC can provide, however other equipment like cooling, storage etc. will need to be made redundant as well.

The alternative costs for a back-up generator including synchronization, frequency control and load management is found to be approximately € 10 500,- scaled to 60 kW system, see Table 12. The costs for a 60 kW UPS is found to be € 45 000,-.

| **Hard ware costs** | | | **Life time** | **Yearly costs** |
|---|---|---|---|---|
| Hard ware costs | €/kW | € | year | €/y |
| UPS | € 750 | € 45 000 | 5 | € 9 000 |
| Load control | € 100 | € 6 000 | 15 | € 400 |
| Synchronisation | € 25 | € 1 500 | 15 | € 100 |
| Frequency control | € 50 | € 3 000 | 15 | € 200 |
| | | | | |
| **Total** | **€ 925** | **€ 55 500** | | **€ 9 700** |

*Table 12 – Reference hardware costs back-up power*

For the diesel generator we assume the following:

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| | | |
| Diesel generator | 60 | kW |
| Investment | 96,000 | € |
| Life | 15 | y |
| annual rent | 6,400 | €/year |
| fuel cost | 86 | €/year |
| O&M | 2,000 | €/year |
| | | |
| **Total annual costs** | **8,486** | **€/year** |

*Table 13: Annual cost diesel generator*

In addition, the reliability and availability of the electricity grid combined with a SOFC will probably be higher than for diesel generator. For datacenters and server equipment we assume the following.

Assuming the server space value increases by 20% for a higher reliability and 30% can be accounted to the power supply. Based on the rental price for server space in The Netherlands which is approximately 20 k€/y for one rack. One rack consumes approximately 5 kW total (including auxiliaries), so the power of 60 kW SOFC is sufficient for 12 racks. This amounts to a total rental price of 240 k€/y. The value increase becomes 20% x 30%x 240 k€/y = 14k€/y.

Total prime power benefits can be more than 30000 € per year.

### 6.1.6 Other assumptions

| Parameter | Type | Source |
|---|---|---|
| | | |
| Value CO2-rich gas without pollutants | Fixed | Based on value in Netherlands: 70 €/ton |
| CO2 price | Fixed | Assumed 25€/ton |
| Biogas price | Fixed | Assumed natural gas -50% (Netherlands) |
| LPG gas | Fixed | 0,78 €/L. 1L = 6,9 kWh (Netherlands) |
| Landfill gas | Fixed | Assumed equivalent to natural gas. We assume that the gas is cleaned if needed and ready to go. |
| Hydrogen gas | Fixed | 5€/kg, 33 kWh/kg |
| DC savings | Fixed | Assumed 10.000 saved in DC/AC inverter + 6% efficiency gain |
| max kW peak charge reduction | Fixed | Average grid operators Netherlands. 20€/kW/y |
| Peak capacity tariff reduction | Fixed | Average grid operators Netherlands. 13€/kW/y |
| Low-Nox zones | Fixed | Reformer SCR costs 400 € per kWe for a gas engine |
| Avoided grid costs | Fixed | Avoided grid enhancement on individual and local level. Costs very dependent on local situation. Range is 7,5-35 k€. |
| Providing flexible capacity | Fixed | Netherlands: 140€/kW/year for primary reserve and 20€/kW/year for secondary reserve. Available reserve should be for up and down regulation, so SOFC can provide max 15 kW of flexible capacity. Both primary and secondary reserve markets are momentarily not accessible for sub-megawatt systems. |
| Local grid support | Fixed | Delivering balancing services like reactive power. Valuable in some countries. Finland: 3000€/year. |

*Table 14: Sources used in analysis*

## 6.2 Value drivers

The C50 can be used in applications with multiple value drivers. To get an idea of the relative position of all the value drivers a graph is shown indicative values per driver for a baseload consumer of heat and electricity. Value drivers are based on assumptions from Table 14.

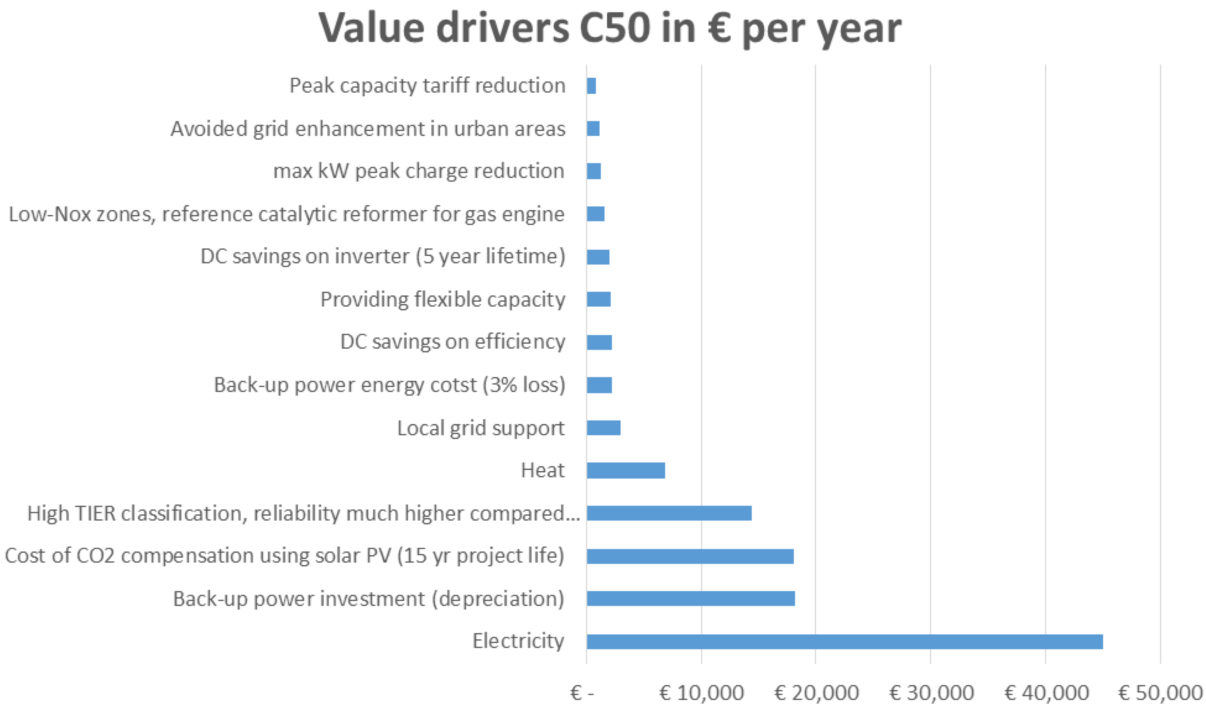



*Figure 32: Overview value drivers*

As clearly visible, the most important value driver is the electricity price including subsidies where relevant. The fuel cell has a high electrical efficiency, which is positive considering that the value of heat is significantly less than the value of electricity.
A system running 8760 hours will produce around 525 MWh of electricity. For a good business case, an electricity value of 20 ct/kWh or higher is needed. The focus should therefore be on applications with high electricity value (including subsidies) or applications with prominent value drivers like backup power.

A demand for flexible capacity is increasing due to the energy transition. The fuel cell provides decentral power production, capable of providing local flexibility and lightening the stress on the electricity grid.

Biogas is a growing market too, with high subsidies in several countries. The CODE2 project6 indicates large climate change mitigation potential due to biogas run CHP systems. Several feedstocks are available: manure, straw, forestry, municipal solid waste etc. Fuel cell systems with high electrical efficiencies create the most value out of these feedstocks.

### 6.2.1 Comparison of different heating configurations

The value of the heat produced varies significantly with the different heating configurations. Based on the described heating configurations from Chapter 3 (see table 5), the yearly heating revenues for specific heating applications and system combinations have been determined.

| Applicaton | Description |
|---|---|
| | |
| Reference CHP | Fuel cell delivering elektricity and hot water, see Par. 3.5.1 |
| CHP increased HEX | CHP with larger heat exchanger, see paragraph 3.5.2 |
| Heat pump | Fuel cell coupled to existing heat pump, see Par. 3.5.2 |
| HVAC coupling | CHP coupled to HVAC system, see Par 3.5.5 |
| Adsorption chiller | CHP with cooling option similar to adsorption chiller, see Par. 3.5.6 |
| Dessicant and humidificatio | CHP coupled to HVAC and dessicant wheel for dehumidification, see Par. 3.5.7 |

*Table 15: comparison of SOFC applications and combinations*

The energy prices are based on actual commercial prices at 2015 including transport, capacity fee, and energy taxes for specific consumers in the Netherlands.

| Energy prices | | User type | | |
|---|---|---|---|---|
| | *units* | **Large** | **Medium** | **Small** |
| Heat (high temp.) | *€/GJ* | 10 | 14 | 20 |
| Electricity | *€/MWh* | 60 | 80 | 150 |
| Cooling | *€/GJ* | 2 | 4 | 8 |

*Table 16 – Assumed energy prices based on small, medium and large users. These rates include taxes, transport fee, etc.*

This different configurations were modelled economically leading to the following result:

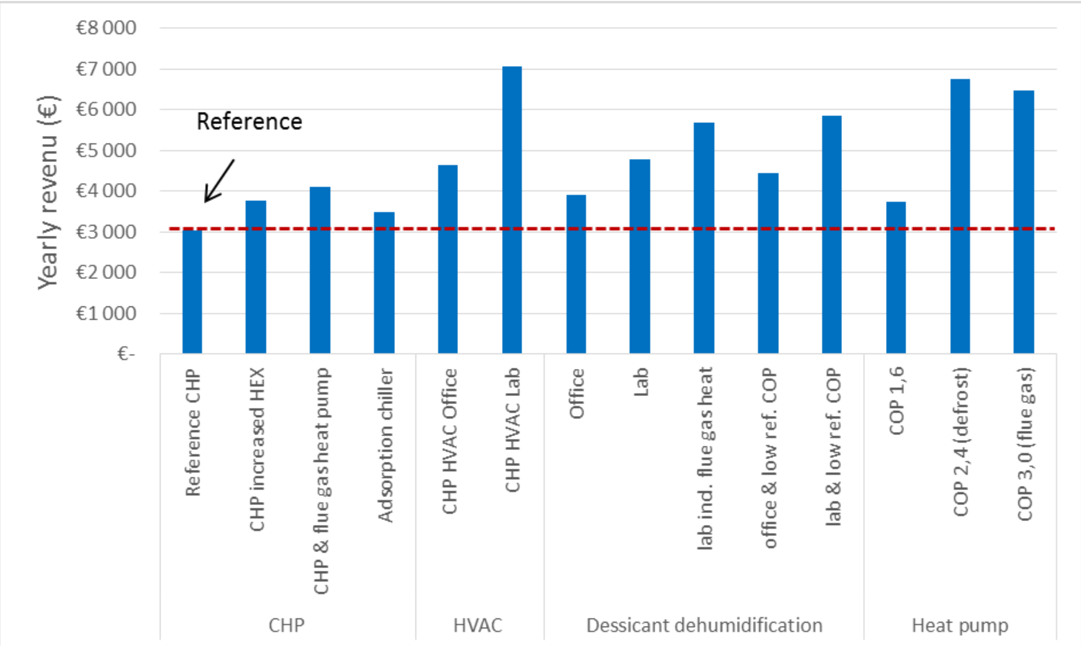



*Figure 33 – Yearly revenue of different SOFC applications based on actual current electricity and heat costs for medium size energy users i.e. medium energy prices.*

The figure shows that the heat pump, lab HVAC and desiccant combination have a higher revenue than the other systems. Since these results only include a specific set of energy prices, the results have been determined for small, medium and large energy users, e.g. shops, hotel and industry respectively. The assumed energy prices are shown in Table 16 and serve as an example for the influence of energy prices on the different configurations.

Figure 34 shows the influence of a higher energy price based on energy prices for small users. The yearly revenues for small users are higher since the energy prices are higher (this is true for most, but not all EU countries). The revenues for the "heat pump COP 3,0 flue gas" configuration have increased compared to the "CHP HVAC lab" configuration. The revenue of this specific heat pump configuration has increased, since the revenues consist of reduced electricity consumption compared to the reference heat pump system. For situations with relatively high electricity prices the heat pump configuration is favorable.

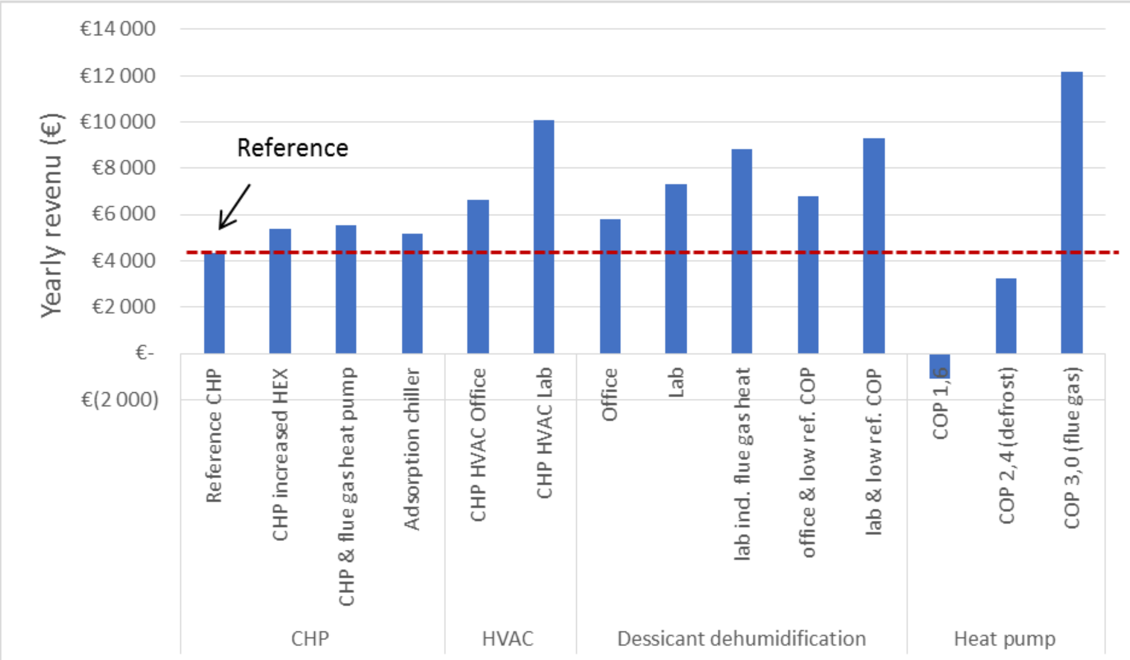



*Figure 34 – Yearly revenue of different SOFC applications based on actual current electricity and heat costs for small sized energy users i.e. high energy prices.*

Figure 35 shows the influence of a lower energy price based on energy prices for large users. For these energy prices the heat pump and desiccant configurations are more economically favorable. The option for which flue gas heat is directly used shows a relatively high revenue. However, for this configuration there is risk of poisoning the supply air with high levels of $CO_2$ (carbon dioxide). For a standard heat wheel configuration, a certain amount of air leakage is permitted, normally a few percent. This causes an unallowable increase in $CO_2$ concentration of the supply air, unless leakage is less than approximately 0,1%[8]. In fact any increase of $CO_2$ for supply air is unfavorable since the capacity of a HVAC system is directly or indirectly based on $CO_2$ reduction for the designated areas. There exist specific heat wheel configurations which reduce the amount of cross flow leakage, but the risk of leakage is most likely not permitted for safety reasons. Therefore this options may only be applied for specific industrial processes such as a drying process.

[8] Assuming $CO_2$ concentration of 10% in return air and an allowable increase of 100 ppm for the supply air $CO_2$ concentration.

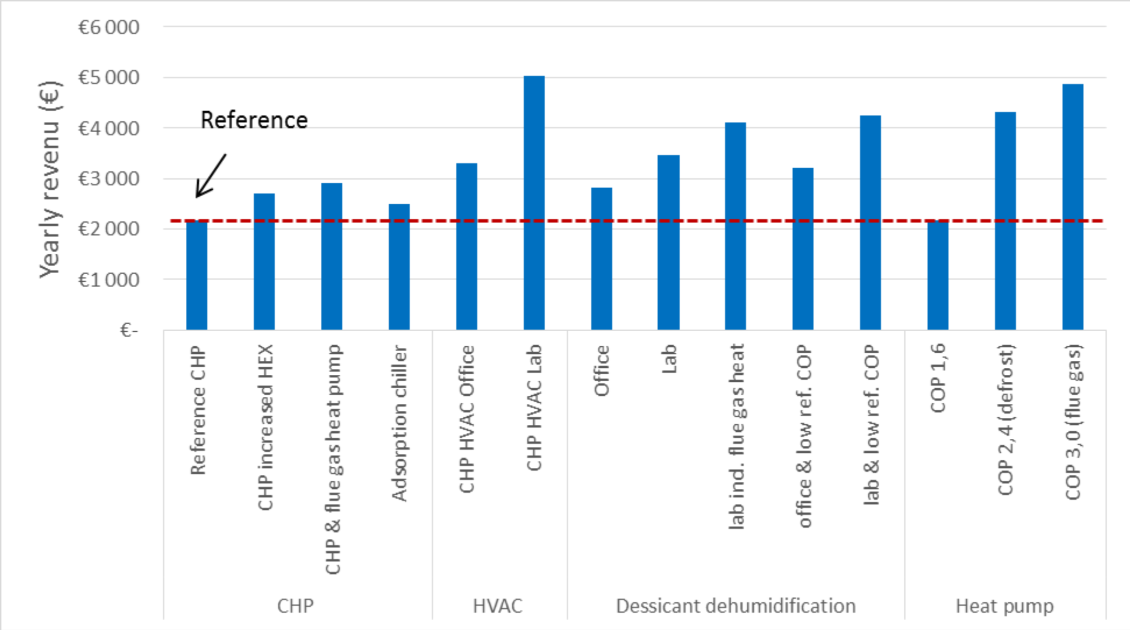



*Figure 35 –Yearly revenue of different SOFC applications based on actual current electricity and heat costs for large energy users i.e. low energy prices.*

## 6.3 Cost drivers

The C50 is currently produced in very small series. We have assumed the following parameters:

| | |
|---|---|
| Investment cost | For the early commercial systems as developed within INNO SOFC, we assume the following cost: 2000 €/kW for the stack and 2000 €/kW for the balance of the plant for early production systems. In addition to the hardware 50.000 euros are added for project design and installation |
| Operation & Maintenance cost | 0,073 €/kWh based on 30 000 hours lifetime, 2000 €/kW stack replacement & 5%/y of balance of plant (BOP) investment (2000 €/kW). |
| Fuel cost | We assume a gas price based on the Eurostat data for the chosen country and size. For general calculations, a value of 0.35 €/m3 is used. |

Over a project duration of ten years, the yearly costs of the C50 are equally divided over these three components: investment, maintenance and fuel costs.

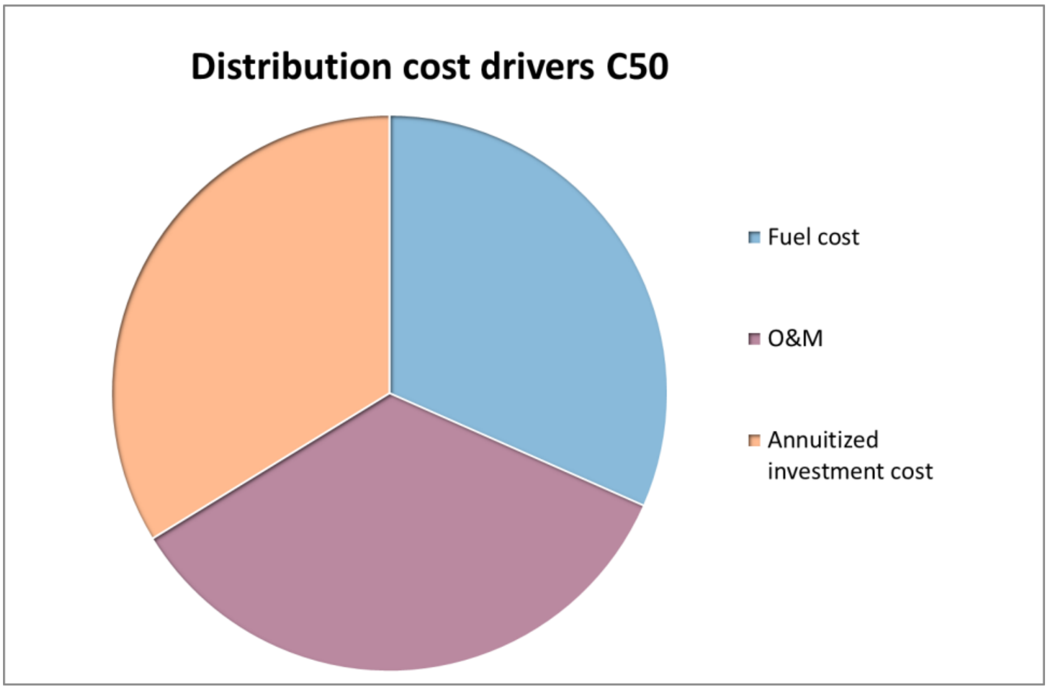



*Figure 36: Indicative cost distribution for an C50 fuel cell system over 10 year project period*

Capex (investment) includes annuitized investment costs based on a 10 year project duration. Maintenance is assumed 5% on the balance of plant components and also includes stack replacement after 30.000 hours of operation.

Reducing the cost of the stacks is crucial, both to limiting initial operation but also to limit maintenance costs (stack replacement). Increasing stack lifetimes will significantly reduce the annual costs.

## 6.4 Case studies

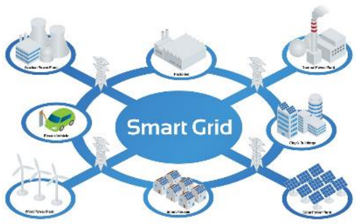
Several promising applications have been selected from a longlist of 60 possible applications. These applications can become 'launching customers', driving down costs so other applications become available. As noted before, energy prices, subsidies and value drivers vary greatly throughout the EU. For these case studies, the following assumptions have been made:

- Gas price 35 ct/m3
- Heat value: 35 ct/m3 = 0.0394 €/kWh
- Load hours: 8760 per year

| Large apartment complex with direct delivery to end-user Error! Bookmark not defined. | |
|---|---|
| An interesting application is to deliver electricity directly to the end-user, so called ‘behind the meter’. This way energy tax can be omitted, creating a better business case. This can be applied to apartments but also offices/stores. The business case can be improved even further if there is a heat grid available. Several example projects exist in Germany and the Netherlands.  | |
| Characteristics | • Full electricity load hours<br>• Electricity sold directly to each apartment<br>• Runs on natural gas<br>• Very high electricity price: 20 ct/kWh |
| Key value drivers | • Electricity for self-consumption: €90.000 per year<br>• Heat: €12.000 per year (if heat grid)<br>• Total: €100.000 per year<br>• Average revenue: >20 ct/kWh electricity produced |
| Consideration | • Extra metering, hardware and software needed<br>• New concept, tax compliance issues may apply<br>• Gas connection will not suffice, compressor needed |

## Smart-grid CHP operated by aggregator

In our changing energy market, aggregators will operate energy generators installed at their clients, and sell the energy to the client. These local, sustainable energy grids can even be independent from the main grid. The value of energy is high because electricity is either generated behind the meter or sold directly to customers saving energy taxes in some cases. The fuel cell supports the renewable smart grid and provides prime power.




| | |
|---|---|
| Characteristics | • Full electricity load hours<br>• Full heat load hours (to heat grid)<br>• Runs on natural gas<br>• Medium electricity price: 12 ct/kWh |
| Key value drivers | • Electricity for self-consumption: €78.000 per year<br>• Heat: €6.000<br>• Replacing generators: €8.000 per year<br>• Total: €92.000 per year<br>• Average revenue: 18 ct/kWh electricity produced |
| Consideration | • Only if energy tax can be avoided<br>• Added value possible for flexibility trading |

## Biogas CHP application with subsidy schemes

Several countries, including Greece and Italy, have favorable subsidy schemes for biogas produced electricity with rates above 10 ct/kWh electricity produced (see Paragraph **Error! Reference source not found.**). Applications include breweries and sugar and dairy industry, where biogas is usually available.

| | |
|---|---|
| Characteristics | • Full electricity and heat load hours<br>• Runs on biogas<br>• Low electricity price: 9 ct/kWh<br>• Attractive subsidies available |
| Key value drivers | • Electricity for self- consumption: €45.000 per year<br>• RES subsidy: €50.000<br>• Heat: €6.000 per year<br>• Total: €100.000 per year<br>• Average revenue: >20 ct/kWh electricity produced<br>• Sustainability (i.e. CO2 reduction) can be an important selling point. |
| Consideration | • Interesting business case |

## Prime (DC-) power for small server rooms and data centers [9]

The C50 can replace diesel generators, switching gear and UPS systems, providing reliable and clean prime power for customers. Clients are willing to pay for reliability, so increasing the reliability (i.e. the TIER value) of the server room will generate extra income. The SOFC increases efficiency by at least 5% due to direct DC power. A sufficient gas grid connection might not be available.

| | |
|---|---|
| Characteristics | • Full electricity load hours<br>• No heat use (optional HVAC coupling)<br>• Runs on natural gas<br>• Medium electricity price: 9 ct/kWh |
| Key value drivers | • Electricity for self-consumption: €45.000 per year<br>• Heat: €0<br>• Replacing generators, switch gear and UPS: €18.000 per year<br>• Reliability: TIER upgrade €14.400 per year<br>• DC power added value: €9.500 per year<br>• Total: €87.000 per year<br>• Average revenue: 17 ct/kWh electricity produced |
| Consideration | • Investment subsidy likely needed<br>• Gas connection not suitable, compressor needed<br>• Willingness to pay for reliability uncertain |

| Hotel with backup power requirement | |
|---|---|
| A hotel has a continuous heat and power demand. The C50 is an excellent baseload system for this application, and can replace diesel generators, switching gear and UPS systems. A sufficient gas grid connection might not be available. |  |
| Characteristics | • Full electricity load hours<br>• Full heat load hours (hot water, HVAC or pools)<br>• Runs on natural gas<br>• Medium electricity price: 9 ct/kWh |
| Key value drivers | • Electricity for self-consumption: €45.000 per year<br>• Heat: €6.000<br>• Replacing generators, switch gear and UPS: €10.000 per year<br>• Reducing kW peak charge: €2.000 per year<br>• Total: €62.000 per year<br>• Average revenue: 13 ct/kWh electricity produced |
| Consideration | • Gas connection not suitable, compressor needed |

# 7 MARKET OUTLOOK

This chapter describes the foreseen development of the C50 and puts these results in perspective of different market applications.

## 7.1 System price projections

Cost of a fuel cell system consist of balance-of-plant (BoP) costs and cell stack costs. Cell and stack manufacturing cost is strongly dependent on production volumes as potential for manufacturing automation and associated material yield improvement is high. In high production volumes, cost of fuel cells approaches a base cost determined by mainly materials and is anticipated in multiple studies to represent approximately 1/3 of overall costs of a system at commercial level. Roland Berger study[10] on stationary SOFC systems highlights this fact (see Figure 38). Since the same cells and stacks can be used in different fuel cell products with different power ranges, cost reduction is dependent on *the overall demand* for the stacks. BoP costs, on the other hand, constitute of more generic cost items such as welded structures, heat exchangers, pre-reformer reactors, insulation material, air blowers, power electronics and automation hardware. On the BoP side, generic means of industrial production engineering, learning and sourcing in masses are anticipated to bring down the costs.

The development of the C50 has already been quite impressive in terms of technical performance and costs. Figure 37 shows the progress made in the past years.

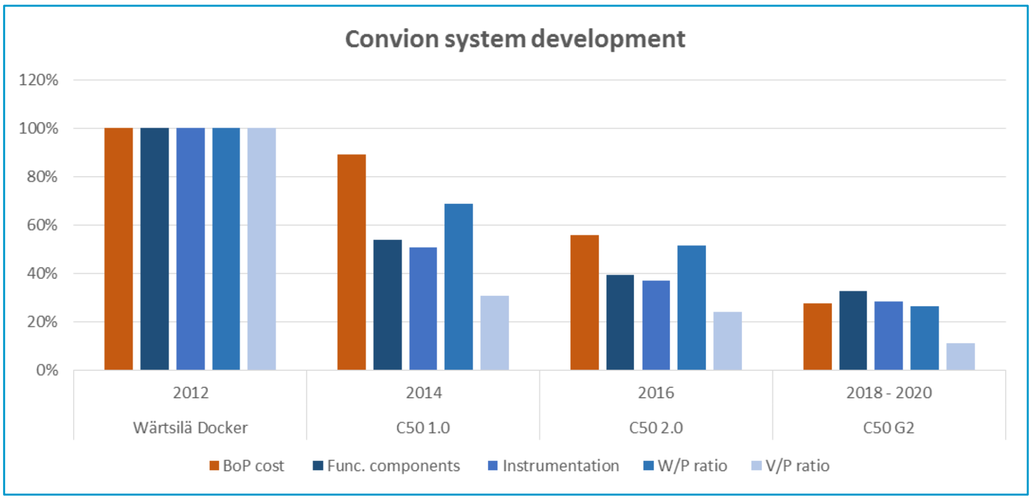



*Figure 37: progress system development C50 Convion*

Convion SOFC systems are multiple stack fuel cell systems and, compared to typical micro CHP SOFC systems, rather large. Convion has approached the system integration and balance of plant and process design with economies of scale in mind and has been able to simplify and to reduce parts count at the same time for building the potential for reliable autonomous operation with long maintenance intervals. Convion concept minimizes cost items that linearly scale by system power output and/or

[10] Advancing Europe's energy systems: Stationary fuel cells in distributed generation, Roland Berger, 2015.

mostly constitute of material costs. Therefore, estimated BoP cost reduction by production volume is faster than that estimated by Roland Berger in a study of a generic 50kW fuel cell system for commercial buildings and therefore rate of cell stack cost reduction will be a major determinant on reaching of the commercial cost level.

The system design developed during the INNO SOFC project will exploit the full potential of Convion's simple, yet non-compromising system concept and represents a leap forward in simplicity and cost and facilitates better application integration than its predecessors. Improvements and optimizations of system efficiency will exhibit higher returns on investment as operating costs of the system are bound to be dominated by fuel cost.

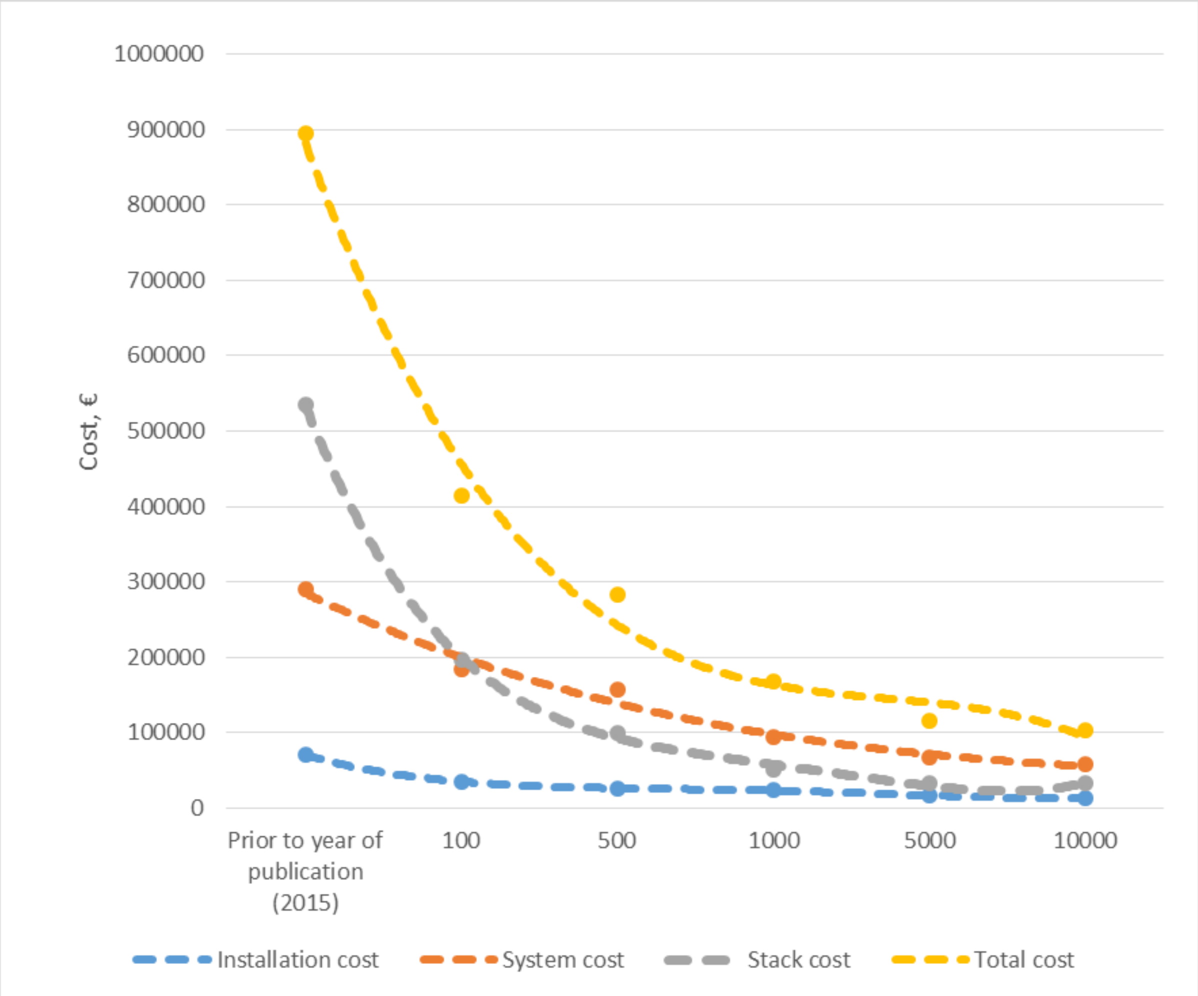



*Figure 38 Itemized breakdown of a generic SOFC CHP system costs as a function of production volume. (Roland Berger study)*

However, the C50 is still at an early commercial stage where volume effects can have a dramatic effect on the capex. Our assumption is that the cost price reduction will have the same character as the trajectory that was outlined in a European wide commercialization study performed by Roland Berger, which is depicted in Figure 39.

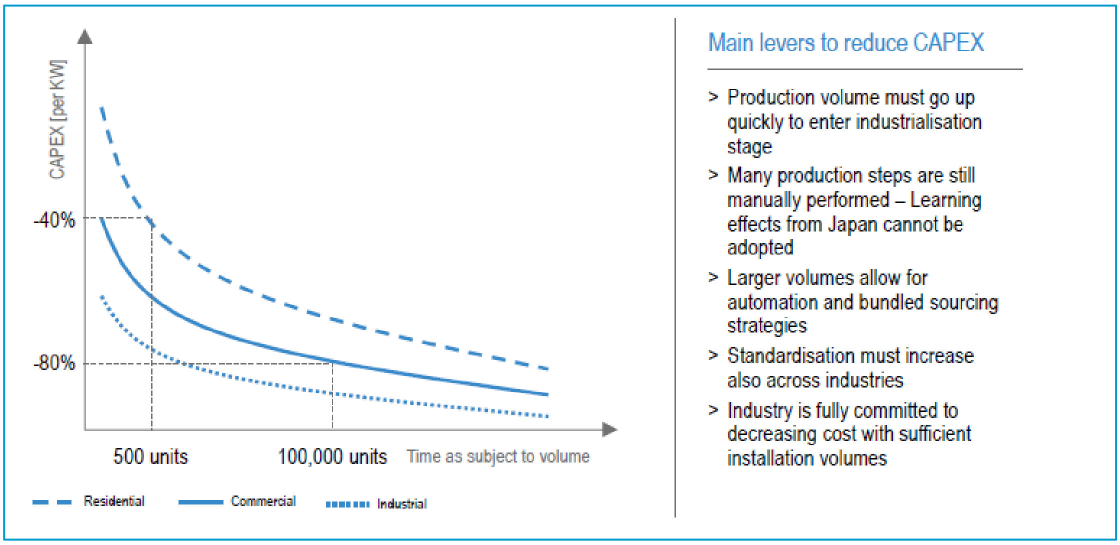


*Figure 39: Anticipated cost reduction and potential levers with volume uptake and learning effects (Roland Berger study)*

These outcomes are sustained by various suppliers in the market that have researched their own cost down potential. For example, Solid Power claims a 70% cost down potential when scaling up to a production volume of 1000 units/year.

## 7.2 From niche to mass market

How does this cost down potential relate to possible applications in different EU countries? We have investigated three stack cost price levels and three market segments (see Table below).

| Stack price level | | Market description | |
|---|---|---|---|
| Current | 100% | Niche | Early adopters (technology)<br>NPV >0 over 10 years<br>Willingness to take risk |
| Small series | -40% | Early markets | Top 3 best cases<br>SPOT < 7 years |
| Mass production | -80% | Mass market | SPOT < 5 years<br>Risk averse |

*Table 17: characteristics of cost down potential and typical market segments*

For niche markets we assume an eager customer segment that likes new technology and is willing to accept a business cases that results in a positive cash flow after 10 years. For early markets we look at top 3 market segments in Member states where energy prices are high, with incentives for (bio)-CHP or local emission restrictions in which customers accept a Simple Pay Out Time (SPOT) of seven years or less. For the mass market we look at average energy prices for different applications and customers that accept a SPOT of 5 years or less. Figure 40 shows the markets that become available if stack costs reach certain levels. Assuming full load hours, constant stack price during project duration and a fixed balance-of-plant cost, we simulate which price levels are needed to reach a business case for each market.

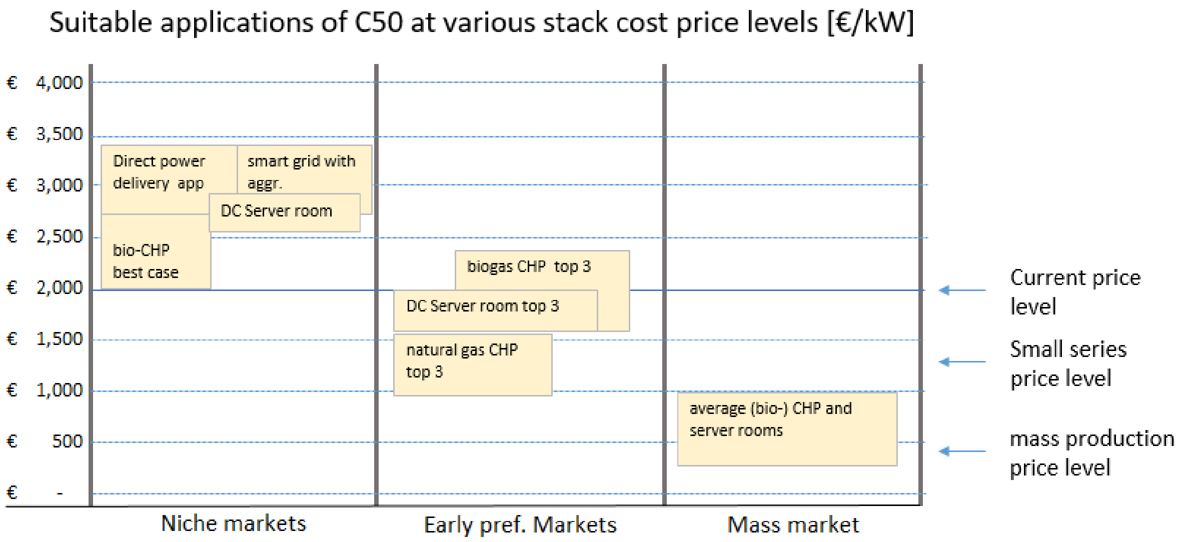



*Figure 40: Impact cost down perspective*

Figure 40 shows that the cost down potential suits the need to reach different markets. At current prices several some niche markets are interesting. At early series production, a broader group of customers can be reached. When mass production levels can be achieved, a broad set of applications around the EU becomes available. Direct power delivery to apartments is a special case and is not allowed in all EU countries. A smart grid with an aggregator (see Paragraph 6.4) could benefit highly from a clean fuel cell if tax regulations allow direct power delivery.

# 8 Conclusions & recommendations

## 8.1 Conclusions

Solid oxide fuel cell (SOFC) technology is a clean, efficient, easily scalable and flexible means for power generation. Efficiency at which SOFC's convert energy of a hydrocarbon fuel to electricity in a single cycle is highest amongst all technologies. Additionally, conversion efficiency of a SOFC system is independent of power generation scale. This makes SOFC an ideal technology for distributed power generation, as it enables continuous and dependable small scale power generation parallel to the grid at the lowest fuel consumption and, consequently, the lowest variable costs compared to alternatives. Benefits of locality of power generation, such as secured power supply, omission of power transmission losses and a possibility to utilize exhaust heat, improve the application feasibility further.

The Convion C50 is a unique, versatile and multi-applicable system and one of the very few reliable, continuous power generators in the sub MW range. The C50 fuel cell has a much better environmental performance than competing technologies such as gas engines or heat pumps. With its back-up power ability, it matches the need in many EU countries for reliable, clean, flexible and zero-emission power production.

Convion C50
- Ultra high efficiency
- Reliability
- Fuel Flexible, both natural gas and biogas
- Zero emission


Match EU markets
- Connectivity with existing buildings due to high temperature heat
- Relief of local E-infrastructure
- Increase of local reliability

The C50 boasts an impressive number of 15 possible value drivers. The ability to run on biogas and to provide backup/prime power add the most economic value, together with the production of electricity for self-consumption (especially for small consumers). With these value drivers, a host of applications can be distinguished.
Multiple system configurations for making optimal use of the heat exist, from which combining the system with an existing heat pump or to a laboratory HVAC system seem the most interesting. Electricity is by far the most important value driver, but heat can be interesting to create a superior environmental performance.

At current prices the C50 is already interesting for three niche applications that have a widespread market potential around the EU: Small server rooms, Smart grid CHP and Bio-CHP.

Due to the current high capital costs level, the fuel cell needs to be placed in these premium markets to benefit from its competitive advantages. Clients with a high electricity price or a (biogas-) CHP subsidy are the first prospects. Examples include apartment complexes with direct delivery to end-user, specific smart grids with direct power delivery, DC powered server rooms and mission critical applications or biogas driven systems in EU Member states with high subsidies (for example Greece, Italy).
These markets can serve as a route to series production, which will lead to drastic cost reductions and consequently opens up new markets.

## 8.2 Recommendations

Potential end-users need to be informed well on the characteristics and possible system configurations of the C50, because of the many possible value drivers. A web based tool will be developed within INNO SOFC to create a good interface between Convion and possible end-users.

Some applications are already interesting, we recommend to finish the product as soon as possible and to analyses market segments in more detail. We recommend to investigate possible routes for reaching customers, reaching partners (for example utilities and aggregators and project development). If series production can be reached, the stack and system cost can be lowered drastically.

## APPENDIX: LONG LIST OF APPLICATIONS

| APPLICATION |
|---|
| Agricultural biogas plant |
| Airports, control tower/ ATC |
| Breweries |
| Chemical plants (little, for prevention of coagulation) |
| Chloralkali industry |
| Cinemas |
| Clean rooms |
| Cold storage |
| District flex energy plant |
| Drinking water production well |
| Electricity network companies (backup) |
| Extensive horticulture |
| Feed e-mobility |
| Financial districts (banks, insurance companies; backup) |
| Food and beverage industry |
| Gas pressure reducing station |
| Gas pressure regulation stations |
| Government (city)buildings with power secure demand (backup) |
| Health care center |
| Hospitals |
| Hotels |
| Industry |
| Intensive horticulture |
| Landfill gas |
| Large apartment complex |
| Large printing companies |
| Military |
| Museums |
| Near zero energy apartment |
| Near zero energy office |
| Off-gas container park |
| Offices |
| Oil platform |
| Pharma industry |
| Plastic injection molding companies (little, for prevention of coagulation) |
| Ports, locks and draw bridges (backup) |
| Poultry farming |
| Prison |
| Remote Island, farmer |
| Remote telecom |
| Server rooms |

Short shipping
Slaughterhouses
Smart grids with aggregators
Supermarkets/buildings with HVAC
Swimming pool
Train-/railway-, Metro- and Bus-Stations (backup)
Universities (multiple units)
Warehouses
Water reservoirs (backup)
Wellness center
Wood drying companies
WWTP with sludge digester (food & beverage, waste processor)