

Life Cycle Assessment of solid oxide fuel cell systems for data centers

A comparative study between three fuel alternatives: natural gas, biogas, and hydrogen

Master's thesis in Industrial Ecology

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CHALMERS UNIVERSITY OF TECHNOLOGY

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In collaboration with RISE ICE Data center

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Abstract

The aim of this thesis was to evaluate the environmental performance of the solid oxide fuel cell (SOFC) BlueGEN BG-15 manufactured by Solid Power. To conduct this study, an attributional Life Cycle Assessment (LCA) was conducted to compare three fuel alternatives to be fed into the SOFC. This thesis was conducted in collaboration with RISE ICE and it is part of two European Union projects that deal with using fuel cells to provide reliable prime power for data centers. The research question to be answered was: “*What is the environmental performance of a SOFC run with three different fuels: biogas from food waste, natural gas and hydrogen?*”.

To answer this question, the system was studied from cradle-to-grave using data provided from the manufacturers as well as literature. Biogas is locally produced from food waste in Sweden, natural gas comes from imports to Italy and the hydrogen is manufactured by electrolysis using electricity from the Italian energy grid. The different processes were modelled in the LCA software SimaPro. The database used was EcoInvent 3.7 and Environmental Footprint 3.0 was the impact method selected.

The environmental impacts were evaluated for climate change, particulate matter, acidification, water scarcity, fossil fuels resource use and minerals and metals resources use. A contribution analysis to check the possesses with the highest environmental burden was done. Also, a sensitivity analysis was conducted to evaluate how the impacts change when renewable energy is used to produce the hydrogen.

Results revealed that fuel production is responsible for most of the impacts. Only mineral and metals resource use is mostly affected by manufacturing the SOFC. Comparing the three fuel alternatives, hydrogen has by far the highest environmental impact. Biogas has the lowest climate change impact and fossil fuel resource use. For the remaining categories biogas and natural gas impact is similar.

The environmental impact from hydrogen depends on the production pathways considered and could become an environmental competing alternative if renewable energy is used to produce it. This way, climate change impact would be reduced. However, other impacts linked to each energy source may arise.

The thesis concluded with some mitigation measurements as well as possible areas of improvement for future research on this area.

Key Words: SOFC, LCA, sustainability, biogas, natural gas, hydrogen, energy, renewable energy, data center, electricity, power, fuel cell.

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1. Introduction

1.1. Background of the study

In recent years, developing clean energy technologies has become a priority. It is highly relevant not only for the environment and climate change mitigation, but it will also contribute to a more sustainable and resilient society and economy (Declaration to support the Green and Digital Transformation of the EU, 2021).

In line with the Paris Agreement, the European Green Deal roadmap aims to achieve 2030 climate target plan of cutting greenhouse gas emissions by at least 55% and becoming carbon neutral by 2050. To reach this key target, existing ambitions aim to increase at least 32% the share of renewable energy and improve energy efficiency by at least 32.5% (European Commission, n.d.).

The Information and Communication Technology sector, commonly known as ICT, which also includes data centers, is responsible for 5-9% of electricity use, and generates 2% of the global CO₂ emissions (European Commission, Directorate-General for Communication, 2020). This is for example in the same order as the contribution of the aviation sector. Servers, cooling systems and storage drivers are responsible for the highest share of energy directly used in data centers. As the world is consuming more and more data together with technological advances such as cloud computing or artificial intelligence, data centers are estimated to have the fastest growing environmental impact from across the ICT sector (Avgerinou et al, 2017).

Therefore, data centers need to become more energy efficient, reuse waste energy generated as well as shift towards more renewable energy sources. One way to contribute to this goal could be to use fuel cells as data centers energy converters. This will also make a data center more flexible and less dependent on using power from the electricity grid.

Today, energy supply is dominated by fossil fuels accounting for 81% of the supply (IEA International Energy Agency, 2020). As a result of the severe environmental impacts arising from conventional power generation systems, fuel cells could be a promising alternative. Previous environmental studies conducted, concluded that this technology might offer a reduction in emissions of greenhouse gases and air pollutants together with high energy conversion and storage (Abdelkareem et al, 2021). In addition, if the fuel fed to these systems comes from renewable sources, fuel cells would facilitate the transition towards renewable energies, contributing to a more sustainable energy system (Melideo et al, 2019).

A fuel cell is a device that offers a conversion of chemical energy into power via an electrochemical reaction between an oxidant (usually O₂) and a hydrogen fuel. All fuel cells are made up of four main components: cathode, anode, electrolyte, and an external circuit. Since its invention by William Grove in 1839, several discoveries made a lot of progress on this technology (Akinyele et al, 2020). This led to different types of fuel cells available in the market and a wide range of possible applications. In the transport sector automobiles, buses, scooters, and ships have been demonstrated to work with fuel cells. Fuel cells can be used for stationary purposes covering a wide range of power, making it possible to use them for either home or industrial applications. There are some cases that both power and heat generated from the fuel cell might be utilized, increasing its overall efficiency (Gandiglio et al, 2019).

This technology has benefits which makes it interesting as a competitor to conventional power generation technologies. These include high energy conversion efficiency, low operating cost, possibility of using a broad range of fuels (both from renewable and non-renewable sources), steady current generation provision and energy security as well as noiseless operation (Abdelkareem et al, 2021). There are five major types of fuel cells. These are Phosphoric acid fuel cell (PAFC), Polymer electrolyte membrane fuel cell (PEMFC), Alkaline fuel cell (AFC), Molten carbonate fuel cell (MCFC) and Solid-oxide fuel cell (SOFC). They differ in the

electrolyte used, operating conditions, fuel that is converted, required load and the application they are used for (Abdelkareem et al, 2021).

Fuel provisioning is an essential task for fuel cell operation. Most of the FCs developed today use hydrogen directly or fuels containing hydrogen, what is called a hydrogen carrier. According to Singh et al (2018) most stationary fuel cells operate using fuels more available than hydrogen such as natural gas or biogas.

Fuel cells have a high potential for environmentally friendly energy conversion; hence, it is expected clear environmental advantages in the applications of this technology (Upadhyaya et al, 2004). However as stated by Upadhyaya et al (2001), it is possible that technologies which exhibit good performance in the use phase, lead to high environmental impacts during the manufacture phase. The main reason is the need of more material intense components. Therefore, to evaluate the environmental impacts of these devices, it is necessary to conduct an environmental assessment that also evaluates the construction, as well as material acquisition and end-of-life phase, and the use of different types of fuels.

Life cycle assessment (LCA) is an established and standardized method which considers the whole product system: fuel sourcing, manufacturing, use phase/operational phases and the disposal (Gandiglio et al, 2019). LCA is a methodology continuously in use to analyse the effects of changing the implementation and use of technologies related to energy (Singh et al, 2018). Furthermore, LCA results can be used to identify improvement possibilities to make the alternatives studied more environmental-friendly (Baumann et al, 2004).

Considering the different types of fuel cells previously mentioned, PEMFC and SOFC are the most mature technology of this type in the market and offer good prospects to use as power source for data centers. PEMFCs are attractive because of their low operation temperature, high-power density and good start-stop capabilities. On the other hand, SOFC are characterized by fuel flexibility, nonprecious metal catalyst and high quality of the waste heat produced that can be used for cogeneration applications (Singh et al, 2018).

Fuel flexibility guarantees the ability of running the fuel cell depending on existing energy legislation, the fuel's availability and its market cost. Also, heat recovery is being explored as an opportunity for managing energy as well as generating savings in data centers. Therefore, it is of high interest to explore the use of SOFC as energy converter technologies to use in data center.

1.2. Literature review and research gap

Fuel cells are considered a promising energy converters technology available today (Abdelkareem et al, 2021). A proof of the raising interest in this technology can be seen by the increasing amount of scientific literature analysing the life cycle of fuel cells that has been generated in recent years. This is shown in Figure 1.

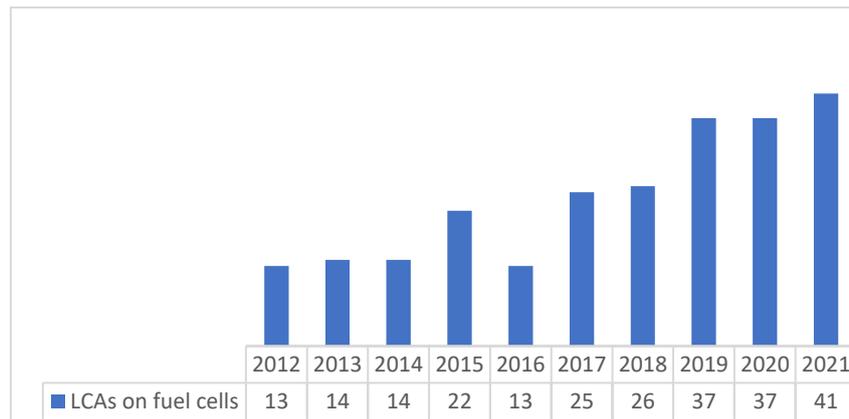


Figure 1. Papers published in Scopus searching for "LCA" AND "Fuel cell" between 2012-2021. Searched on 02/02/2022

Focusing on SOFCs, there are several studies that analyse the use of different biofuels, the integration of SOFCs with wastewater treatment plants or the impact of the energy mix used, as some examples. The main outcomes of some articles that analyse the environmental aspects of fuel cells are presented in the following paragraphs.

Quantification of the ecological benefits from replacing conventional diesel with biofuel derived from local available waste feedstock is performed by Lin et al (2013). SOFCs are seen as a promising alternative technology to be used as auxiliary power unit for heavy truck during rest intervals. This study compares energy consumption and green-house gas emissions of different fuel pathways using LCA with thermodynamic analysis. The system boundaries are set from waste-to-electricity (WTE). These include collection and transport of waste feedstock to processing sites, processing the waste into bio-fuels and, its distribution and conversion into auxiliary electricity within the SOFC system. It concludes that methane derived from municipal solid waste (MSW) achieves the lowest total GHG emissions (0.09 kgCO₂eq) to generate a unit of auxiliary electricity (1 kWh) and has a relative high system efficiency. Fuel converting process dominates the environmental impacts in terms of energy consumption and GHG emission.

Rillo et al (2017) performed an LCA of a 250 kW_e SOFC system fed with biogas sourced from sewage treatment and compared it with using natural gas from the grid as well as with traditional natural gas-fed combined heat and power (CHP) technologies: an internal combustion engine and micro gas turbine. It used 1 kWh of electricity generated as functional unit. The analysis includes both the biogas production in the anaerobic digester and SOFC manufacturing, operation and maintenance. Therefore, it is followed a "cradle-to-gate" approach. Three scenarios are analysed: feeding the SOFC with natural gas from the grid, feeding it with biogas from the wastewater treatment plant and making use of carbon capture technology. Making a comparison of the scenarios, biogas is more beneficial than natural gas when considering climate change and fossil depletion, however for acidification potential, photochemical oxidant formation and particulate matter the trend is different: natural gas shows the best performance. This is linked to anaerobic digester operation since it is an energy intense process. Also, when comparing internal combustion engine, micro gas turbine and SOFC natural gas-fed CHP technologies, this last option presents the best performance in all the impact categories considered.

Moretti et al (2020) made a cradle-to-grave analysis (from raw materials extraction to the final dismantling and waste treatment) of a 199 kW SOFCs fuelled by biogas coming from wood chips, wood pellets and *Mischantus* pellets (a mixed of perennial grasses). Two functional units were defined: 1 kWh of electricity and 1 MJ of heat. It is a novel technology in early stage of development that combines biomass gasification with SOFCs to produce electricity and heat. Results showed that fuel production and transport are responsible for the highest environmental

load. The next highest impact contributor was the stack, due to its material and energy requirements during the manufacture phase. Anyhow, the biogas option has about 37-95% lower environmental when comparing it to conventional natural gas CHP generation (using boilers and the German electricity grid), especially in climate change, photochemical ozone formation, acidification and terrestrial eutrophication.

Lee et al (2015) conducted a cradle-to-grave life cycle assessment of a 100 kW-class SOFC CHP system fed with natural gas and compared the impacts associated with different sources of electricity. Results revealed that the SOFC stack is a major contributor to the environmental impact associated with the manufacturing phase (72% of the impact comes from the stack, while the remaining balance-of-plant (BoP) components are responsible of the other 28%). Fossil fuel depletion, particulate matter formation, human toxicity and climate change are the categories with the highest impact for the SOFC stack. Also, it was found that depending on the different energy mixes of electricity used to manufacture the system, the environmental impact changes considerably. Energy mixes of electricity generation that use coal have the largest impact. Concerning the comparison of manufacturing, operation and disposal, the operation phase is responsible for 89.9% of the overall impact

Al-Khori et al (2021) conducts an LCA for a system that integrates SOFCs into natural gas plants to raise its efficiency and reduce greenhouse gas emissions. It is a cradle-to-grave study with a lifespan of 10 years and a functional unit of 1 MW electricity output. The SOFC is fueled by natural gas. Results show that the operation phase mainly contributes to the total global warming potential (GWP), acidification potential and human health particulate air impact categories whereas manufacturing affects in higher proportion eutrophication potential, ozone depletion air and human toxicity. Also, it should be pinpointed that anode slurry preparation as well as the fuel blower are the stages that most impact these categories.

Gandiglio et al (2019) carried out a cradle-to-grave assessment of the environmental impacts of a biogas-fed 10 kWel-SOFC integrated in a wastewater treatment plant and compares it with a reference scenario where all the electricity needed is purchased from the grid and a third scenario using a prethickening machine for the sludge. The system analysed scales data from similar studies as Rillo et al (2017). Manufacturing and maintenance of the SOFCs CHP system and operation of the wastewater treatment plant (WWTP) are the life cycle phases included in the system boundaries. The study brought electricity requirements for the WWTP operation as the key elements influencing the environmental impacts of this system. This result is in line with Rillo et al. LCA results.

Abdelkareem et al (2021) reviewed the environmental aspects of fuel cells and revealed that in almost all the environmental impact categories FC technologies present better performance than conventional power generation systems. The comparison between different types of FC technologies brought molten carbonate and solid oxide fuel cells as the relatively more environmentally friendly ones, compared to proton exchange membrane. This can be perceived in the impact categories of global warming potential, particulate matter formation, photochemical oxidant formation, terrestrial and freshwater eutrophication potential, mineral resource scarcity and water consumption potential. SOFC and MCFC are able to use the fuel directly as they have internal reforming capability, therefore there is no need for precious metals in the electrodes. In addition, for SOFC commonly the impacts mainly depend on the type of fuel used and how it has been produced.

Table 1 summarizes the most relevant information regarding definition of the system and outcomes of the previous literature discussed.

Table 1. Literature review summary

Literature	Type of system	F.U.	System boundaries	Main outcomes
Lin et al (2013)	Replacement of conventional diesel with biofuel derived from local available waste feedstock	1 kWh of electricity generated	Cradle-to-gate of the fuel (does not include SOFC manufacture)	Fuel converting process dominates the environmental impacts in term of energy consumption and GHG emission
Rillo et al (2017)	250 kWe SOFC system fed with biogas sourced from sewage treatment	1 kWh of electricity generated	Cradle-to-gate	Biogas and natural gas alternatives environmental performance varies depending on the impact category
Moretti et al (2020)	199 kW SOFCs fuelled by biogas coming from wood chips, wood pellets and <i>Mischantus</i> pellets	Two functional units: 1 kWh of electricity or 1 MJ of heat	Cradle-to-grave	Fuel production followed by the stack manufacture, contribute the highest to the environmental load.
Lee et al (2015)	100 kW SOFC CHP system fed with natural gas and compared the impacts associated with different sources of electricity	1 kW electricity generated	Cradle-to-grave	Depending on the energy mixes of electricity used to manufacture the system, the environmental impact changes considerably
Al-Khori et al (2021)	System that integrates SOFCs into natural gas plants	1 MW electricity output	Cradle-to-grave	Anode slurry preparation as well as the fuel blower are the stages that most impact the categories considered
Gandiglio et al (2019)	Biogas-fed 10 kWel-SOFC integrated in a wastewater treatment plant	Wastewater treated by the plant in one year	Cradle-to-grave	Efficiency of the system and energy consumed by the WWTP are the key elements influencing the environmental impacts of fuel cells

All these studies demonstrate that LCA is a consolidated technique to assess the environmental performance of SOFCs. Most of them mention the type of fuel used as one of the main contributors to the environmental load of this technology. Hence, in order to make this study as complete as possible, not only is it of interest to include the manufacturing and operation stage of the fuel cell stack and balance of plant but also the fuel life cycle.

1.3. Fuel alternatives justification

Natural gas network is widely extended and dominant in several countries in the EU (Eurostat, 2019) as historically, together with coal, it has been the main fuel used to generate electricity in traditional thermal power plants (Neuman et al, 2021). Natural gas has recently been labelled as green energy by the European Commission, to bridge the transition towards renewable energies (European Commission, 2022). However, this was a controversial decision as it is a fossil fuel mostly made up of methane, which is a particularly strong greenhouse gas, and leaks from gas

pipelines and infrastructure might occur. Therefore, this policy can be seen as a delay for the energy transition that boosts a “carbon lock-in”, leading fossil fuel to remain the primary energy source for at least the following decades (Al-khori et al, 2021).

On the other hand, after presenting several LCAs on fuel cells, it is observed that using biowaste to manufacture biomethane and feed it to SOFCs is a feasible alternative. Since more than 20% of the total food produced is lost or wasted in Europe (Eurostat, 2018), converting it into biogas is an interesting end-of-life treatment that transforms it into a renewable and valuable product. This follows the Circular Economy principles.

Furthermore, blending hydrogen in natural gas is seen as an opportunity to reduce emissions compared to using natural gas alone. It was not found any previous study analysing the impact of feeding hydrogen directly to SOFCs. Since hydrogen produced through clean pathways is starting to be seen as a major player on the decarbonization of our society, it seems necessary to evaluate this alternative.

Hence, it is considered relevant to study and assess the impacts of fuelling SOFCs with natural gas, biogas and hydrogen. No study comparing the use of biogas coming from food waste with using natural gas and hydrogen manufactured by electrolysis was found. Therefore, it is decided to carry out an LCA on fuel cells which are run with these three different fuel options based on the technology available in the present moment.

1.4. Aim and problem formulation

The aim of this master thesis is to assess the environmental impacts of fuel cells used as energy converters in data centers when using natural gas, biogas, and hydrogen as fuels, while creating a life cycle model that can be integrated in other projects or LCAs.

To perform this study, an attributional LCA will be conducted, and each case will be studied from cradle to grave. Figure 2 shows the different life cycles phases included in a cradle to grave analysis. The model developed is as a proof-of-concept in the framework of two EU projects in which RISE Research Institutes of Sweden is involved:

- E2P2 (January 2021 – September 2024): an EU project that seeks to “develop and demonstrate low environmental impact fuel cells that provide economic and resilient prime power solutions for data centers in populated areas” (E2P2, 2022). It aims to create an energy efficient and quiet solution using fuel cell technologies for on-site power generation that can compete with conventional technologies for urban digital infrastructure and reduce costs. RISE is the project coordinator. Participants involved are companies from Italy, Germany, The Netherlands, and Switzerland.
- WEDISTRIC (October 2019 – March 2023): an EU project that “aims to demonstrate that district heating and cooling systems can be built on a combination of renewable energy sources and waste heat recovery solutions” (Kulemetieva, 2021). The solution proposed seeks to contribute to the decarbonization of urban heating and cooling systems and provide a solution for sustainable living. The demonstration case validated by RISE involves a cogeneration system which integrates a fuel cell. The electricity output is used to power the data centers whereas the excess heat is supplied to the existing District Heating network. This project involves participants from Spain, Denmark, Romania, Sweden, Germany, France, Italy, Austria, Croatia, and Poland.

E2P2 and WEDISTRIC include a “Sustainability analysis” work package to highlight the environmental impact of the developed technology in each project. This task involves assessing the whole data center in combination with the fuel cell, however the scope of this study only focusses on the fuel cell itself. Therefore, later it can be integrated in the whole LCA of the design concept.

Both projects are founded under Horizon 2020 (H2020), the second biggest EU Research and Innovation programme (*What is Horizon 2020?*, 2017). The main audience is the EU consortia; however, as H2020 is a programme open to everyone, it is also relevant to customers, product developers, policy makers and general public.

The main research question of this study is:

“What is the environmental performance of a SOFC run with three different fuels: biogas from food waste, natural gas and hydrogen?”.

Sub-questions such as *What fuel is preferable? What part of the fuel cell system life cycle has the highest environmental load? What are possible improvement opportunities? and What impact reduction actions should be prioritized?* will provide a guide on finding the information to answer the main research question.

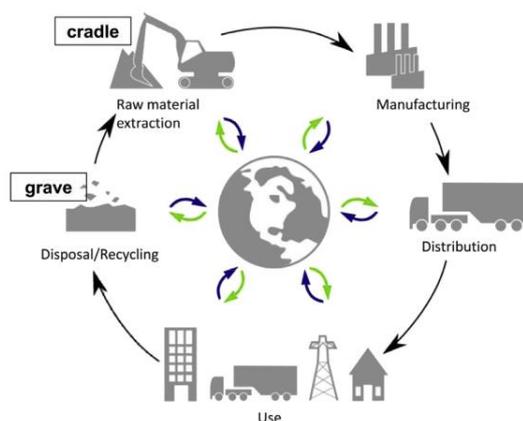


Figure 2. Conceptual drawing showing the stages involved in a "Cradle to Grave" analysis. (Lee et al, 2015)

1.5. General methodology

The LCA is performed according to the standard ISO 14040 which includes: definition of the goal and the scope, life cycle inventory analysis, life cycle impact assessment and the interpretation phase. The whole analysis is an iterative process: going back and forward within the four different steps.

In order to assess the independent systems, an attributional LCA is performed for the three fuel alternatives: biogas from food waste locally produced in Sweden, natural gas imported to Italy and hydrogen manufactured by electrolysis using electricity from the Italian grid. Data is collected directly from FC manufacturers, fuel providers and direct measures from a SOFC in ICE RISE test site. For the data that could not be retrieved, assumptions based on literature were made.

The results of the assessments are compared against each other. Data from the inventory analysis was used to make a model of the systems making use of the software SimaPro and EcoInvent 3.7 data base. The impact assessment method selected was EF 3.0.

Based on the results obtained, two sensitivity analysis are conducted to deal with uncertain data concerning the inventory as well as to compare the environmental performance of using different energy sources to manufacture hydrogen. Lastly, the results are interpreted, discussed and improvement measures are suggested.

2. Theory

2.1. Solid Oxide Fuel Cells

Solid oxide fuel cells are highly efficient devices to convert chemical fuels directly into electrical power. A SOFC is made of three essential parts: a porous cathode, a porous anode and an impermeable electrolyte. The operation temperature is given by the temperature that the electrodes need to achieve the desired ionic conductivity. They are part of the high-temperature technologies as they operate between 600 – 1100 °C (Damo et al., 2019).

The main operating principle of SOFCs consists in feeding air to the positive electrode (the cathode), producing the reduction of the oxygen. The electrolyte initiates the transfer of the oxygen ions from the positive to the negative electrode (the anode). Water is formed when the oxygen ions react with the fuel fed to the negative electrolyte, producing the fuel oxidation at the anode. Then, the free electrons flow through an external circuit from the negative to the positive electrode generating a current (Akinyele, 2020).

A scheme of the operating principle of SOFCs is shown in Figure 3.

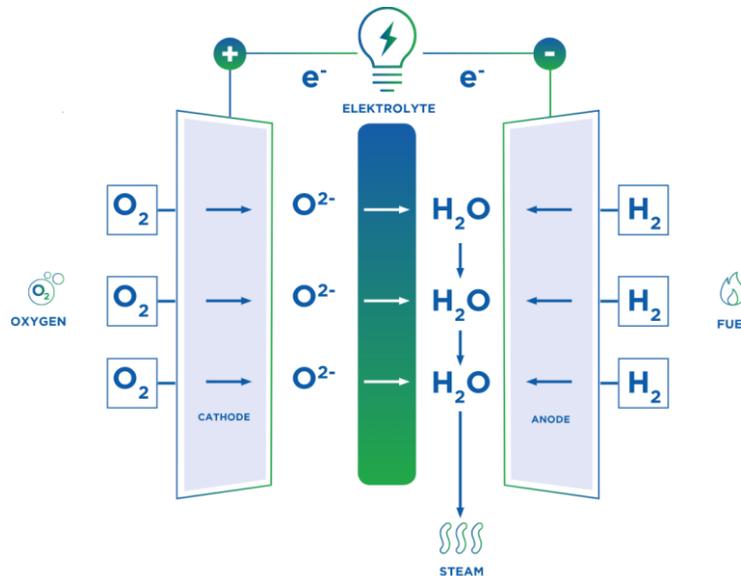


Figure 3. Scheme of the operating principle of SOFCs (Solid Power, n.d.)

The electrochemical reactions taking place are the oxygen reduction at the cathode (Equation 1) and the fuel oxidation at the anode (Equation 2).



Fuel to electrical efficiency of SOFC is around 60%, which could go up to 85% if the excess thermal energy produced during the reaction is utilized for cogeneration applications. In addition, SOFCs are the most sulphur-resistant FC technology as their toleration to this chemical compound is orders of magnitude higher than other cell types (Office of Energy Efficiency & Renewable Energy, n.d.). Furthermore, carbon monoxide does not poison the system, which can even be used as fuel. Hydrogen containing fuels such as natural gas, biogas, coal gas and propane, among others, can be used as the high operation conditions in the FC allows direct thermal reforming. Also, operating at high temperature removes the need of using a noble catalyst in the operational arrangement, hence cost is notably reduced (Akinyele, 2020).

However, in the other side of the coin, the main disadvantage with this technology is the high temperature at which it operates. Therefore, only a limited selection of materials is found to be thermally, catalytically and conductively stable at that temperature. High-temperature corrosion issues can be mitigated by using protective layers and specific material in the cell arrangements; however, these usually tend to be expensive, and its environmental impact needs to be evaluated (Abdelkareem et al., 2021).

Fuel cell units will directly generate direct current (DC) power in the range of 45-50 V and an internal booster will be used to rise the output DC voltage from the range 45-50 V to 380 V, more suitable to couple with battery packages or other module components (E2P2 Grant Agreement, 2020).

2.1.1. SOFC stack components

Electrolyte

SOFCs are commonly made up of a nonporous solid ceramic electrolyte as zirconium oxide. This one is usually stabilized with yttrium oxide, namely, yttria-stabilized zirconia (YSZ). Through YSZ, ions flow from the cathode to the anode (Akinyele, 2020). Yttrium is usually added as a dopant, allowing a good conduction of oxygen in the operating range temperature (Longo et al, 2017).

Cathode

Regarding the cathode material selection, it is important that it fulfils some characteristics such as thermal stability, stable ionic conductivity and catalytic activity (Abdalla et al, 2018). Lanthanum Strontium Cobalt and Iron Oxide (LSCF) fits all these characteristics and is commonly used in SOFCs' cathode.

Anode

On the other hand, anodes are generally porous ceramic-metallic (known as cermet) composites of an electrolyte. It is relevant for the anode material that it speeds up the fuel oxidation reaction and hence nickel-based yttrium-stabilized zirconia (Ni-YSZ) is often utilized (Abdelkareem et al., 2021). This allows full oxidation of the fuel hydrogen. Also, YSZ's low cost, immiscibility in each other and their non-reactiveness within a broad range of temperatures, make it a good alternative.

Interconnects

The main function of interconnectors is to recover electrons and to transfer them from the anode to the cathode in fuel cells. Requirements for selecting the appropriate materials are good stability in both oxidizing and reducing atmospheres, good electrons conductivity as well as chemical and mechanical compatibility with the electrolyte. For temperatures in the range 800-1000°C ceramic interconnectors (strontium/calcium-doped La CrO₃) are used, whereas metallic interconnectors are preferred for operation below 750°C. In the case of metallic interconnectors, ferritic steels and Cr-based alloys are the common choice (Longo et al, 2017).

Sealing

It is required to use sealants which are stable in a wide range of oxygen partial pressures together with minimizing thermal stresses when operating at high temperature. It is possible to use either rigid or compressive seals for SOFC. Compressive seals are usually made of metal or modified mica-based material whereas for rigid seals usually glass ceramics are used (Longo et al, 2017).

2.1.2. Type of SOFCs

Common SOFC design types are planar crossflow and tubular counterflow. Planar cells are the ones widely adopted as they can be upscale to large stacks at high power density. Regardless of its design, a single SOFC cell generally produces voltages not higher than 1 V. Therefore, a series

connection of single cells (what is called stack), is formed to obtain higher power (Singhal, S.C., 2011). This different cell arrangements can be visualised in Figure 4.

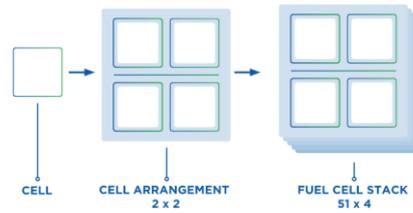


Figure 4. Fuel cell arrangements (BlueGen technology, 2021)

Making one cell component thicker than the other provides structural stability. Today, Anode Supported Cells and Electrolyte Supported Cells are usually used in commercial applications. On the one hand, a thicker electrolyte favours manufacturing and gives good mechanical stability however the longer path for ion migration results in higher ohmic losses. On the other hand, using the anode as support layer allows lower ohmic losses as the electrolyte is thinner, but there is a higher probability of cracks formation and issues related to gas diffusion. A further alternative is the Metal Supported Cell, also known as MSC. It is a variant of the ASC configuration: the Ni-based cermet is substituted by a ferritic porous layer, resulting in a reduction of costs compared to the use of zirconia ceramic and also allowing for a reduction in the operating temperature (Padinjarethil et al, 2021). In Figure 5 it is possible to observe the different types of cell support.

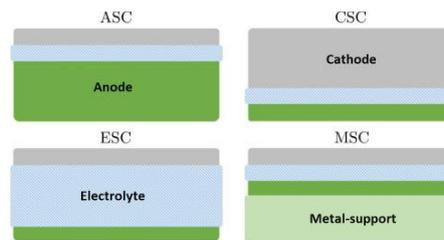


Figure 5. Different types of support for FCs. (Subotic, V. et al, 2021)

2.1.3. Case study: SOFC stack and balance of plant

The FC stack assessed belongs to Solid Power. It is a company based in Trentino (Italy) which was born in 2006. Solid Power is specialized in designing, developing, and manufacturing fuel cell micro-cogeneration systems, also called stationary fuel cells or fuel cells m-CHP. It is a technology that produces both heat and electricity for a building using a single fuel (PACE, 2018). They base these systems on SOFC technology. They work with anode-supported cells with a thin YSZ electrolyte and a porous perovskite cathode. Cells are manufactured by water-based tape-casting and screen-printing processes. The production plant of the stacks is located in Mezzolombardo (Italy) and has a capacity of 8 MW/year (*Technology review - Solid Oxide Fuel Cell*, 2017). The assembly takes place in Heinsberg (Germany), the main site for the European distribution.

This company claims that the cells manufactured are characterised by good mechanical stability, provided by a dense anode structure and no limitation on gas diffusion. Also, they achieve high power densities (1 W/cm^2), utilize more than 80% of the fuel input and can be operated in the temperature range $650 - 800^\circ\text{C}$, which allows the use of different fuels (*Technology review - Solid Oxide Fuel Cell*, 2017).

It was previously mentioned that the LCA of SOFC is part of two EU projects: WEDISTRIC and E2P2. For the first project, nine 1.5 kW BG-15 SOFC are used to produce direct current electricity power as well as heat for potential recovery. On the other side, E2P2 project uses sixteen 6 kW BG-60 SOFC. The only difference between both systems is that BG-60 is made of

four stacks (as the ones used by BG-15). Therefore, the power is four times higher. BG-15 includes all the balance of plant inside the case of each unit whereas the system analysed for BG-60 fuel cells has an external centralized gas and water treatment system developed by Tec4fuels, a partner in the consortia.

The main focus will be a single BG-15 type fuel cell since most of the data obtained was for this model and it is already running in the WEDISTRICCT demo-site in Luleå.

The product analysed, the BlueGEN fuel cell, is a 1.5 kW - scale generator with the high efficiency. It is able to continuously generate electric power at 55% efficiency (lower heating value, LHV). As it has an annual production of 13000 kWh of electricity, this technology is suitable in small commercial applications (*Technology review - Solid Oxide Fuel Cell, 2017*).

Table 2. Technical specifications of the fuel cell BG-15 (Solid Power)

Electrical output	1.5 kW
Thermal output	1.0 kW
Electrical efficiency	55%
Thermal efficiency	40%
Overall efficiency	85%
Stack lifetime	40000 hours
System life	Min 10 years
Cells per stack	70

In Figure 6 it is shown the BlueGEN hotbox opened. The upper part is the stack, made of 70 cells and the down part is the internal reformer.



Figure 6. BlueGEN hotbox: internal reformer and stack) (*Technology review - Solid Oxide Fuel Cell, 2017*)

Stack manufacture involves several steps. Each of them is described on the following lines. Figure 7 shows a scheme of one possible path for manufacturing the stack.

Ball milling is a mechanical technique that is broadly used to grind powders into fine particles. The reactants are generally broken apart using solvent molecules in the traditional method and a slurry is formed (Chaudhuri et al, 2021). Tape Casting is used to obtain thin ceramic sheets from the ceramic slurry previously formed, and it is casted in a thin layer onto a flat surface (Habudillah et al, 2018). After this, usually comes the sintering phase: it is a thermal process to convert fine particles into a solid mass using heat and pressure without reaching the particles' melting point (Lu et al, 2015). Lastly, screen printing is used to fabricate homogeneous layers of pastes containing ceramic powders (Ried et al, 2008). In addition, materials are subjected to plastic deformation to obtain the required size, shape, or change the physical and chemical properties, what is usually called metal forming.

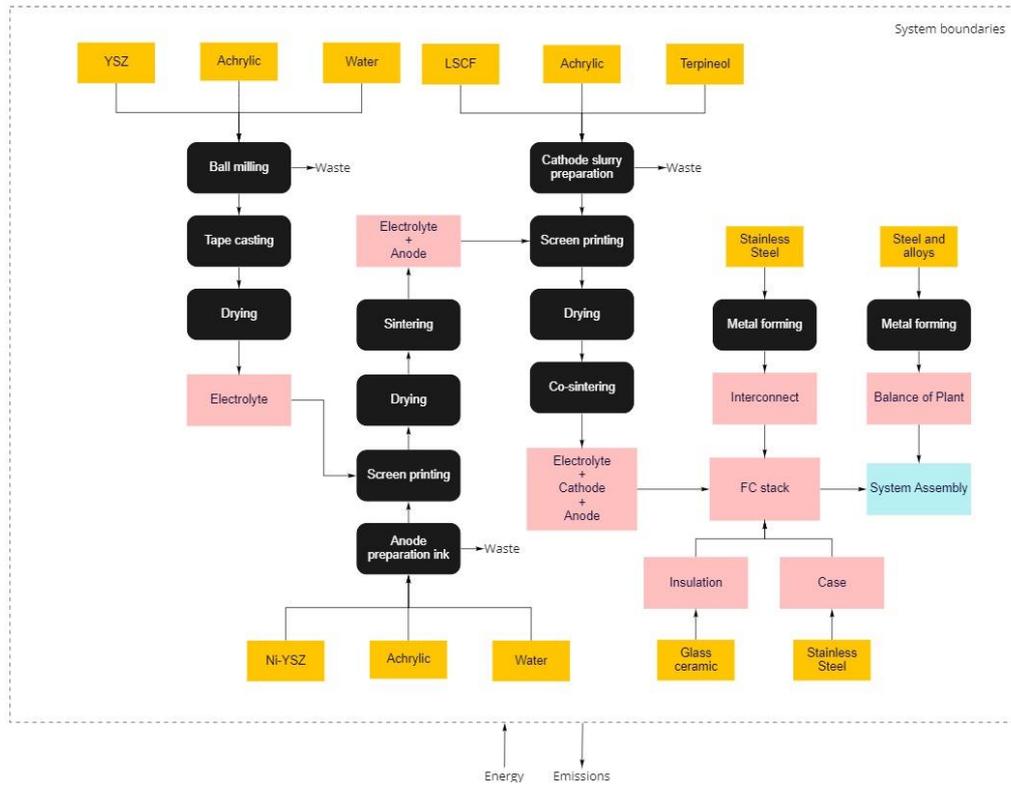


Figure 7. System boundaries of the FC system manufacturing. Based on Al-Khori et al (2021)

The Fuel Cell stack can be said to be the heart of the FC system however, other components are required to process the fuel, supply and manage the air and water, or power conditioning system. This is what is called the balance of plant (BoP).

The SOFC assessed is manufactured by Solid Power and its different parts can be seen in Figure 8. It shows the fuel cell module (2), which includes the FC stack and the hot BoP (internal reforming). The cold BoP includes: a concentric flue adaptor with measuring point (1), a waste heat recovery unit (2), gas safety double block valves (4), a condensate tank (5), the air delivery system (6), a water treatment system (7), a power system (6) and a gas desulphurizer (9).

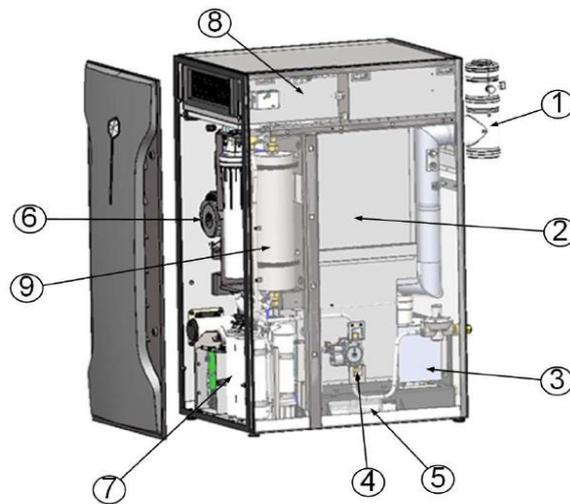


Figure 8. Bluegen BG-15 overview components (Solid Power, n.d.)

The functioning of a SOFC can be visualized in Figure 9.

instance in batteries, and it works as a bridge between the critical load from the utility and a utility proxy like a local diesel generator, until the utility supply returns. This configuration enables the “Five nines” resilience (Grant agreement E2P2, 2020).

However, this configuration brings some problems. On the one hand, the use of diesel generators emits air pollutants and causes undesirable sound levels, which are limited by legislation. On the other hand, utility capacity may be limited or unavailable in the data center location (Grant agreement E2P2, 2020).

Making use of utility proxies such as fuel cells or batteries is an attractive alternative being developed to use in edge data centers. This concept could substitute the traditional UPS to a power converter as fuel cells, which are able to run with different fuel inputs. Cost and emissions could be minimised, together with meeting the high availability requirements of critical applications (Grant Agreement E2P2, 2020).

2.3. Fuels used for SOFCs

The following sections include a detailed description of the cases that are evaluated and compared.

2.3.1. Natural gas system

Natural gas from the Italian grid is directly supplied to the fuel cell system as prime power. The high voltage grid is used as secondary power supply in case of emergency. The advantage of this configuration is that the gas grid is stable and reliable compared to the electrical grid. In addition, gas grid offers buffer capacity in case of unexpected failure as some gas is stored by gravity in the pipes, opposite to an immediate blackout power generation in case there is a failure on the electrical grid (E2P2 Grant Agreement).

Treatment of the natural gas is required before it enters the fuel cell unit. Sulphur (H_2S) is contained in all fuels that originate from natural sources (fossil or biogas). Also, odorants that are sulphur-based compounds are added for safety reasons so in case of gas leakage the gas can be readily detectable and prevent dangerous situations (HSE, 2015). However, these additives poison the stacks by reacting with the anode fuel cell material and deactivate it. This produces layers with high resistivity, leading to a decrease of the fuel cell conductivity and hence the overall performance of the technology is negatively affected. Therefore, it is necessary to have a desulfurization unit before the stack (E2P2 Grant Agreement).

At the same time, it is also required a water treatment system to demineralize and deionize water in order to achieve a very low conductivity. In this process it is removed metal ions such as Ni, Mg, K or Na to avoid impurities. For a safe operation it is required a water conductivity below 0.05 mS/cm at 25°C.

2.3.2. Biogas from food waste and WWTP sludge system

The second alternative analysed consists in using the biogas produced in Boden biogas facility to fuel the SOFC (Figure 11). As mentioned before, SOFCs offer fuel flexibility and biogas is one of the possibilities to generate power using fuel cells.

It is possible to produce biogas from different types of organic waste and biomass: from the sludge generated in wastewater treatment plants, from cattle waste, from food waste or from biogas crops. Moreover, the biogas needs to go through different post-treatment processes depending on its final use. This can be visualised in Figure 10.

Biogas has several applications such as fossil gas replacement, CHP to generate electric energy and heat, injected in the municipal grid or upgraded to natural gas to be used as fuel in vehicles. It can also be stored in smart grids to use during peak demand or low wind or solar energy production (Wastewater treatment - sludge management, 2021).

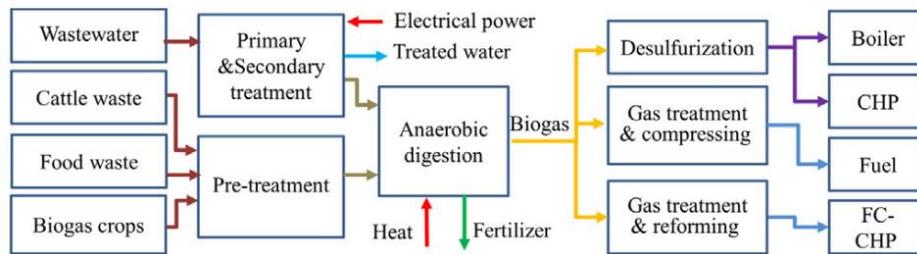


Figure 10. Simplified schematic with the inputs and outputs for energy generation from different types of organic waste (Saadabadi et al, 2019)

The biogas manufactured in Boden comes from the food waste generated in Norrbotten County and the sludge produced in Boden WWTP. Two relevant benefits arise from this alternative. On the one hand, it is avoided its disposal and the waste is transformed into a valuable product to get energy. Hence, when designing out of waste, organic materials are regenerated through a biological process (anaerobic digestion, in this case) and resources are managed in a more effective and sustainable way.

On the other hand, using a fuel produced nearby not only does it substantially reduce transport emissions, but it also does create prosperity in the region: restoring natural capital as well as creating local jobs. Therefore, it brings social and economic benefits.



Figure 11. Boden biogas facility

WWTP sludge

Water used by household needs to be treated to remove organic matter and nutrients. Usually, it is mixed with surface water run-off on the journey towards the WWTP. The combination of both waters is referred to as “wastewater”. Wastewater has to be treated before re-entering the water cycles as it may contain polluting or harmful substances. During the treatment it is obtained a raw sewage sludge which mainly consists of water, organic matter, and nutrients. The sludge also needs to be treated and dewatered. It is estimated that every year a person is responsible for the production of 70 – 100 kg of dewatered sludge (EurEau, 2021).

It is important to treat the sludge to reduce the water content and enhance its hygienic quality. Digestion of the sludge is a common treatment used to stabilise the sewage sludge. It is done in the absence of oxygen (anaerobic conditions) and during this process, biogas is produced. This is a valuable renewable energy source that might be used on-site or exported. Biogas from sewage sludge has a high methane content (around 65%) while the rest is mainly carbon dioxide (Wastewater treatment - sludge management, 2021).

Boden WWTP has a capacity of 30000 pe. It cleans 300 m³/h of wastewater, what means a dewatered sludge daily production of nearly 7 tons (U. Jansson, personal communication, March 2022).

Food waste

Sweden is a pioneering country in food waste recycling. According to Swedish EPA (2020), in 2018, 500 000 tonnes of food waste were collected to treat biologically. This corresponds to 38% of all food waste that is generated in Sweden. Specifically, most of the collected food waste (85%) in Sweden goes to the production of biogas. The biogas generated is usually upgraded to bio-methane. Consequently, bio-methane is used in 95% of Swedish vehicles run with gas (Swedish Energy Agency, 2020).

Swedish EPA (2021) ambitions aim to increase biological treatment to at least 75% of food waste from households, commercial kitchens, shops, and restaurants. Therefore, biogas sector is expected to considerably expand during these years and consolidate as a renewable energy source.

This tendency can already be seen in Boden biogas facility: it has increased its capacity from 150 m³/h of raw gas output to 600 m³/h in April 2022. The biogas produced is cleaned to almost pure methane (CH₄) and is either introduced in the district heating or used as fuel for vehicles. The food waste it receives comes from Norrbottens län. The following lines will describe the different processes to biologically treat food waste.

Pre-treatment

Food waste needs to be grinded, and water is added to get a slurry, to make it possible to pump it and homogenise it. Boden biogas facility can manage between 12000 to 14000 tons/year of food waste, with a total solid content of 30%.

Pasteurization

When the sludge from the WWTP is dewatered and the food waste is grinded and diluted, each type of waste is pasteurized. This is done at 70°C to ensure all virus and pathogens are killed, what is commonly known as pasteurization. Also, this contributes to heating of the feedstock, so the digesters are at the appropriate temperature to produce the gas.

Anaerobic digestion and bio-gas upgrade

The pasteurized feedstock is pumped to a larger vessel called digester where the anaerobic digestion takes place. This process consists in the biodegradation of the organic matter, which is transformed into methane by a mixed community of archaea and bacteria. It occurs under thermophilic conditions ($T > 45^{\circ}\text{C}$) and the retention time is two weeks. A volumetric flow rate of 150 m³/h of raw gas is produced.

The output product is the biogas, mainly containing methane and some carbon dioxide, and the digestate generated. In order to use the biogas obtained, it needs to be upgraded and purified to get a composition and quality similar to that of natural gas (Yliopisto, 2013). Water scrubbing, also known as absorption in water, is the most widely used technology for gas upgrading in Europe. Its basic principle relies on the higher solubility of CO₂ in water than in CH₄. Carbon dioxide is absorbed into the water, increasing methane content in the upgraded gas. Also, this method is effective for H₂S removal (Yliopisto, 2013). Using this technique, Boden biogas facility increases methane content in the gas from 59.5% vol to 96.5% vol.

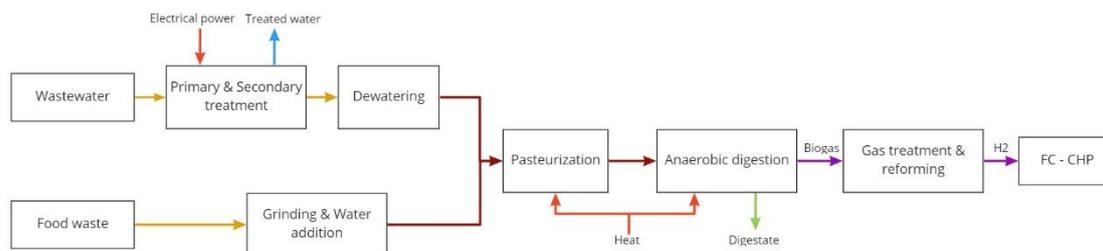


Figure 12. Simplified scheme of energy generation from wastewater and food waste in Boden biogas facility

Waste generated (Digestate)

Digestate material is pumped to a storage tank and stabilized. Then, it is recycled. As it is rich in nutrients, including phosphorous and nitrogen, it is common to use it as a replacement of mineral fertilizers. However, to be allowed to use this digestate as fertilizer in arable land, it is necessary to get a certification which authorizes it. Boden biogas facility still does not have this accreditation, therefore 90% of the digestate is used as landfill cover whereas the remaining one goes to land that it is not used for food production.

Energy requirements

Boden biogas facility is energy sufficient: it uses the biogas produced to provide the energy required in the different treatment processes. As it was not possible to obtain data regarding the amount of energy required by the operation of the plant, for the inventory analysis it was assumed that the plant uses electricity from the grid, according with the model of biogas facilities in EcoInvent.

2.3.3. Hydrogen

Hydrogen is often discussed as a key element in the decarbonization of the energy system. However, currently most of the hydrogen is used for different industry proposes such as ammonia manufacture. Since fuel cells run with hydrogen are being commercialised in several sectors as well as the rising need for storable energy carriers, hydrogen is increasing its popularity. This is shown by the rise on demand for hydrogen by more than three times since 1975 (Ajanovic et al, 2021). Even if its prospects are promising, hydrogen is still a long-term option as its positive impact highly depends on the energy source used for its production.

Hydrogen is a secondary energy carrier. It is obtained from primary energy sources such as fossil, renewable or nuclear energy. Today, the consolidated process for producing hydrogen is the steam reforming of natural gas. IEA (2019) report states that 71% of the hydrogen manufactured worldwide is produced by this alternative, which leads to the emission of 10 kg of CO₂ per every kilo of hydrogen. In addition, the second widest spread way of getting hydrogen is using coal. Hence, almost all the hydrogen comes from fossil fuels which presents a high environmental burden. This is commonly referred as “grey hydrogen”. The share of hydrogen produced through different methods is shown in Figure 13.

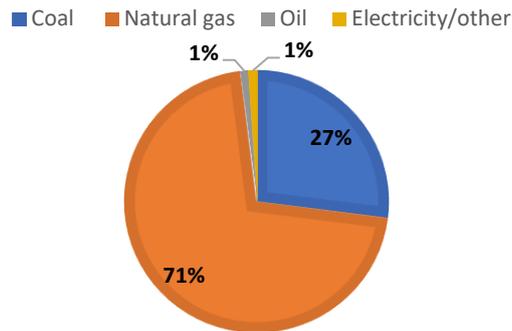


Figure 13. Hydrogen production methods worldwide. Based on IEA (2019)

On the other hand, from a future perspective, it is of big interest the hydrogen obtained from renewable energy sources. This is possible via electrolysis; however, this process requires not only a high amount of electricity but also 10 L of demineralized water per kg of hydrogen produced (Delpierre et al, 2021). This can be problematic in those areas where water is a scarce resource (IEA, 2019). “Green hydrogen” is the name given to this molecule when produced from renewable energies.

Natural gas reforming is a mature technology for obtaining hydrogen and its production cost is lower than electrolysis. Nevertheless, natural gas is becoming more expensive not only because of geopolitical reasons but also due to higher CO₂ emission costs. On the other side, it is expected important learning effects for the electrolysis alternative and its production cost could be exceptionally reduced if hydrogen production is done when there is excess of electricity (Ajanovic et al, 2021). Even if green hydrogen is now a niche technology, if it overcomes its barriers, it has the potential to displace gas reforming and become the new regime for hydrogen production sociotechnical system and contribute to net-zero emissions of the energy system.

Prospects of the spread of hydrogen produced by electrolysis makes it an alternative interesting to assess from an environmental point of view and compare its impacts with natural gas and biogas.

Lack of primary data regarding the different inputs and outputs for this process made it necessary to rely on secondary data. An assessment of environmental impacts of wind-based hydrogen production in the Netherland using ex-ante LCA is used to model water electrolysis technology (Delpierre et al, 2021).

Electrolysis is an electrochemical reaction that uses energy to split water molecules into oxygen and hydrogen. The apparatus where this reaction takes place is called electrolyser. The different setups for electrolysers depend on the operating conditions and the electrolyte used.

Alkaline Electrolyte (AE) uses a liquid electrolyte such as potassium hydroxide. It is a mature technology that has been used in the industry for over a century, mainly in ammonia production. Therefore, it is considered of interest to select AE technology to produce hydrogen. Figure 14 shows the basic operation of AE.

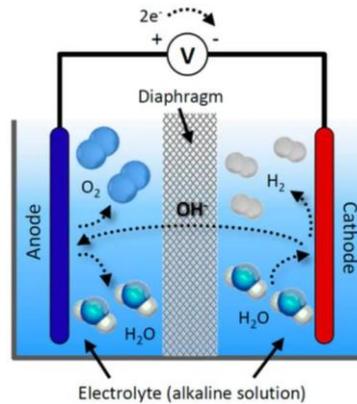


Figure 14. Simplified operation scheme of AE electrolyser (Rodriguez et al, 2021)

2.4. Life Cycle Assessment Framework

2.4.1. A system analysis tool

Environmental system analysis (ESA) assesses to what extent technological solutions meet environmental and resource constraints to transform current technological systems into more sustainable ones (Chalmers, 2021). LCA is an ESA methodology.

It is relevant to pinpoint that a system analysis is not a mere data gathering tool that can be used for any decision nor a complete decision support and not a decision itself. According to Sandén (2007), it must be kept in mind that “systems analysis (and LCA) is a selection and structuring of data to produce relevant arguments in a specific (decision or learning) context”. All in all, system analysis is a kind of collective learning process which produces and communicates relevant arguments.

When using these assessments, it is not the goal to obtain exact numbers, the essence is: “it is better to be roughly right than precisely wrong”. Therefore, during the whole assessment process and during the interpretation of the results, this must be kept in mind.

2.4.2. Steps in LCA

There is a series of international standards to provide the principles, framework, and methodological requirements for performing an LCA, ISO 14040-14043, which have been issued since 1997. In the first year that ISO 14040 was published (1997), LCA was described as:

“LCA is a technique for assessing the environmental aspects and potential impacts associated with a product (...)”.

It consists in four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. LCA is an iterative process, therefore each step is refined as the study goes along and all phases are interconnected. The Life Cycle Assessment framework is shown in Figure 15.

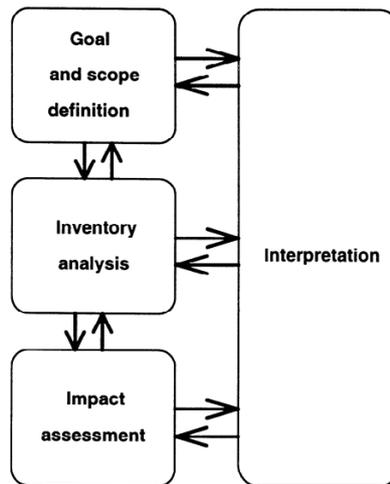


Figure 15. Phases of an LCA according to ISO 14040:1997 standard

In the goal and scope definition it is decided the product that is going to be studied as well as the purpose of the study. According to ISO standards, the goal of an LCA must clearly state the intended application and the reasons behind carrying out the study and the intended audience. Regarding the scope, it should unambiguously specify the functions of the system and select a functional unit in accordance. The functional unit expresses the function in quantitative terms, and it is used as the basis for comparison in comparative studies. Other modelling choices made during the goal and scope definition are the system boundaries, which determine the unit processes to include within the LCA. Types of environmental impacts considered need to be selected and the level of detail also must be specified to enable the goal and scope of the assessment to be met (Baumann et al, 2011).

During the inventory analysis phase, it is built the system model according to the goal and scope defined in the previous step. It involves data gathering, and the calculations to quantify the inputs and outputs of the product system. These data are used as input for the impact assessment (ISO 14040, 1997). In this step, it is built a flow model, usually a flowchart, of the system showing the activities analysed and the flows within them. It is calculated the resource use together with pollutant emission of the system, relating all of them to the functional unit previously selected (Baumann et al, 2011). Also, allocation procedures need to be selected and justified if the systems involve several products. Lastly, calculation of energy flows should consider the fuels, electricity sources used, the conversion efficiency as well as inputs and outputs linked to the generation and use of these energy flows.

Next step, the impact assessment, transforms the data from the inventory analysis into specific environmental impacts. The level of detail, the impacts selected, and the choice of the methodology goes in accordance with what is defined in the goal and scope. It is common to include the following steps: classification, which assigns inventory data to impact categories, characterization, which models the inventory data within the impact categories and, finally, the weighting, giving a relative importance to each environmental impact and aggregating the results (ISO 14040, 1997). Classification and characterization were made mandatory in the standard ISO 14042 2000 while weighting remains optional since it involves ethical and personal values. Therefore, data prior to weighting should remain available (Baumann et al, 2011).

Interpretation of results is of high relevance, since it is where all the results are presented, examined and conclusion are drawn. According to ISO 14040 (1997) findings from the inventory analysis and the impact assessment are combined, generating conclusions and recommendations to the decision-makers. It is pertinent to include a sensitivity analysis to check the robustness of

the results. Also, conducting a hotspots analysis shows how the different stages contribute to the total environmental load and provides information of which processes should be prioritised.

2.4.3. Limitations and criticism

Today, there are several environmental assessment techniques available and LCA is one of them. All techniques have some limitations; therefore, it is highly relevant to know and understand how they work in order to be aware of their weak points during the whole assessing process (ISO 14040, 1997).

Choices and assumptions such as system boundaries, data sources or impact categories might be subjective, based on the commissioner and the practitioner interests and standpoints. Also, the models used for the inventory analysis, or the impact assessment are limited by assumptions and may not include all the potential impacts. In addition, results of the study that focus on global or regional issues might not be accurate if using them for local applications. Data is a key aspect in LCAs as it can be limited by accessibility, availability or quality (data gaps, site-specific or average). Furthermore, there is a lack of temporal and spatial dimensions which may make impact results uncertainty (ISO 14040, 1997).

In addition, Baumann et al (2011) critic LCAs when used by industry as smokescreens seeking to attract attention to the wrong environmental aspect or pushing for environmentally suspect products. Impeding manipulating LCAs for green washing is possible by extending standardization methodologies.

2.4.4. LCA on fuel cells

Within the Joint Research Centre, the Institute for Environment and Sustainability (IES) provides technical and scientific support to EU policies with the aim of protecting and sustainable develop the European as well as the global environment (Stages, n.d.). This institute coordinated two projects: “HYGuide” and “H2FC-LCA” to deliver guidance when doing LCA on fuel cell technologies and hydrogen production systems. As a result, it was created a Guidance Document (GD) that provides information on how to deal with key methodological aspects on LCAs.

This GD is expected to be used in all projects receiving fundings from the Fuel Cells and Hydrogen Joint Undertaking that request conducting an LCA on hydrogen technologies (Masoni et al, 2011). As this is the case for his study, it was taken into consideration the recommendations suggested in this document. However, as this is not a mandatory document but guiding, some different methodological choices can be done as long as they are properly justified.

3. Goal and scope definition

Based on the goal and the scope, this section specifies the requirements on the modelling for the LCA case study.

3.1. Goal and context of the study

As stated in section 1.4 *Aim and problem formulation*, the aim of this study is to find the environmental consequences of using different fuels (natural gas, biogas and hydrogen) to run a SOFC and compare the results obtained between the three options analysed: natural gas imported to Italy, biogas locally produced from food waste in Boden and hydrogen produced by electrolysis using energy from the Italian energy grid. The main research question is:

“What is the comparative environmental performance of a SOFC run with three different fuels: biogas from food waste, natural gas and hydrogen?”.

Other relevant questions that also might be relevant to answer are *What fuel is preferable? What part of the fuel cell life cycle has the highest environmental load?, What are possible improvement opportunities?, What impact reduction actions should be prioritized?.*

3.2. Scope and modelling requirements

3.2.1. Functional unit

As it was previously mentioned in 2.4.2 *Steps in LCA*, the functional unit expresses the function of the system being studied in quantitative terms. It is used as the basis for comparison in comparative assessments. The function of a fuel cell is producing electricity and, in some cases, useful heat. This is what is known as a multifunctional process.

There is not homogeneity regarding the selection of the functional unit (f.u) in previous projects performed (Melideo et al, 2019). Fuel cell’s LCA guides delivered by FC-HyGuide suggest using kWh as f.u only when the scope of the study is the FC stack. If the scope includes the FC system and electricity is the only valuable product, MJ_{electricity} is recommended as f.u. In case both electricity and heat generated are useful products, MJ_{exergy} is the suggested unit. Therefore, the electricity generated from the fuel cell is selected as the functional unit. It will be expressed in terms of kWh instead of MJ_{electricity} as it is the unit usually used in data center, and it will facilitate the communication of the results.

3.2.2. Impact categories and method of impact assessment

ISO 2006b defines impact categories as a “class representing environmental issues of concern to which life cycle inventory analysis may be assigned”. Midpoint impact categories should be selected using an approved methodology together with scientific literature and European policy goals (FC-Hy Guide). “The 8th Environmental Action Programme to 2030” published by the European Commission is the basis to achieve the UN’s 2030 agenda together with its Sustainable Development Goals. In this programme the following are prioritized: climate change, natural resources preservation, ecosystem quality and human health (E.C., 2020).

Most common impact categories chosen in previous LCAs on fuel cells include Global Warming, Acidification, Eutrophication, Photo-Oxidation Formation and Human Toxicity (Smith et. al., 2019). Resource Consumption is also relevant to the priorities of the 8th Environmental Action Plan.

The LCIA method selected is Environmental Footprint (EF). This model was established in 2013 by the European Commission’s Joint Research Centre with the aim of harmonising European methodology for environmental studies using a life-cycle approach (PEF Guide, 2012). It enjoys international acceptance and includes the category indicators considered of relevance. Thus, it is considered appropriate to use.

The recommended models for the EF scheme are summarized in the table below. Also, it should be highlighted that long term emissions occurring beyond 100 years are excluded.

As it was previously mentioned in the theoretical background, ISO standard for LCIA (ISO 14042) states mandatory the impact category definition, the classification and characterization sub-phases. SimaPro automatically assigns the results from the life cycle inventory to their respective impact categories according to the environmental impact assessment selected (this is the classification step) (Baumann et al, 2004). In this case, EF 3.0. Consecutively, the extent of the environmental impact per category is calculated making use of characterisation factors.

Despite not being a mandatory sub-phase, weighting provides support to identify the most relevant impact categories and critical life cycle stages where the focus should be put on. Furthermore, it also facilitates the communication of the results as it aggregates all the information. However, there is not a unique weighting scheme, as it involves value choices. According to JRC technical report (2018), for the EF a hybrid weighting set was developed based on evidence as well as judgements. This also includes aspects related to the robustness of the results. Hence, this enables to highlight the categories for which results are more robust, allowing to make decisions on the most certain results.

The indicator used for each impact category, the unit and the final weighting factor which includes the robustness of the result are presented in Table 3.

Table 3. Impact categories included in the EF impact assessment method (PRé Sustainability, 2021)

Impact category	Indicator	Unit	Weighting factor including robustness (scaled to 100)
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO ₂ eq	21.06
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 _{eq}	6.31
Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTUhu)	CTUh	2.13
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTUhu)	CTUh	1.84
Particulate matter/Respiratory inorganics	Impact on human health	Disease incidence	8.96
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U ²³⁵ _{eq}	5.01
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC _{eq}	4.78
Acidification	Accumulated Exceedance (AE)	mol H ⁺ _{eq}	6.20
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N ⁺ _{eq}	3.71
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P _{eq}	2.80
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (P)	kg N _{eq}	2.96
Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTU _{eq}	1.92
Land use	Soil quality index	Dimensionless (pt)	7.94
Water use	User deprivation potential	m ³ world _{eq}	8.51
Resource use, minerals, and metals	Abiotic resource depletion (ADP ultimate reserves)	mg Sb _{eq}	7.55
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	8.32

To facilitate the handling of data as well as present robust results, six categories were selected out of the sixteen included in the EF impact assessment. The ones selected are described in the following paragraph.

Climate change

This category is related to global warming. Greenhouse gases are characterized based on the extent to which they contribute to the radiative forcing in the atmosphere, i.e. their capacity to absorb infrared radiation and heat the atmosphere (Baumann et al, 2004). Not only carbon dioxide is responsible for climate change, but also methane, chlorofluorocarbons, nitrous oxide and other trace gases contribute to raising Earth's temperature. It is considered relevant to include climate change impact category as it is one of the most studied categories and there is a big worldwide concern on the importance of reducing GHGs emissions.

Particulate matter

This impact category accounts for adverse health effect on humans that may be caused when there is an exposure to respiratory inorganics and its precursors (NO_x, SO_x, NH₃). World Health Organization estimates that 4.2 million people die every year as a result to ambient (outdoor) air pollution (WHO, 2019). Hence, it is found pertinent to consider this category.

Acidification

Most common acidifying pollutants are SO₂, NO_x, HCl and NH₃. Acid deposition occurs when they are trapped in rain, fog, snow, or dew. Acidification leads to fish mortality, leaching of toxic metals out of rocks or soils, and damages to forest and buildings. Acidification is a location sensitive category: it varies depending on where the acidification pollutants are deposited. Both Italy and Sweden have areas highly sensitive to acidification (ICP Waters, 2018), therefore it is an interesting category to include.

Water use

In the last decades, several water systems essential for ecosystems proliferation as well as humans feeding, have become stressed. Freshwater sources like lakes, rivers or aquifers are increasingly becoming more dried and polluted. To mitigate this issue, it is necessary to know what processes or products put the highest pressure on this valuable resource.

Resource use: minerals and metals

This category accounts for the abiotic resource depletion of ultimate reserves. Scarcity of metals and minerals necessary for the technological industry are leading to important shortages of these finite resources. Also, new models of production and consumption which promote a circular economy advocate for minimizing the extraction of materials from the Earth crust. Thus, to account for the use of minerals and metals, this category is included.

Resource use: energy carriers

This category includes the abiotic resource depletion of fossil fuels. This is a relevant category as there is a transition phase from non-renewable resources to renewables ones. Therefore, new policies push for a reduction on fossil fuel used. It is of interest to include this category to analyse fossil's resource use intensity.

3.2.3. System boundaries

System boundaries must be specified in several dimensions. Boundaries between the technological system and nature, geographical area, time horizon, production of capital goods and boundaries in relation to other products' life cycles (Tillman et al., 1994).

3.2.3.1. Boundaries between the technological system and nature

The technical system is made of the activities under human control, which are included in the flow model that can be visualised in Figure 17. When a flow enters or leaves human control, it

also enters or leaves the technical system and, at the same time, leaves or enters the natural system. Therefore, the boundaries between the modelled technical system and the modelled surrounding natural system are also the boundaries that separate the inventory analysis from the impact assessment (Baumann et al., 2004).

The life cycle of the fuel cell system begins with the extraction of the raw materials needed to manufacture the different parts that integrate the technology assessed as well as the water treatment and fuel production to run the system. This is what is considered the *cradle* of this study. From the natural boundaries, inputs are materials and energy. The life cycle study ends up in the *grave*, that is where the EoL treatment takes place and emissions, electricity and heat are the outputs generated that go into the natural system.

The life cycle of the analysed systems can be split in seven different stages:

- 1) Extraction and production of raw materials.
- 2) Production of energy generated for the next step.
- 3) Manufacturing of the stack, the balance of plant and its assembly.
- 4) Installation of the system.
- 5) Operation and maintenance.
- 6) Fuel extraction and processing, the infrastructure required, and the fuel produced.
- 7) Decommissioning, involving recycling, re-use, incineration or landfill of the different parts.

Figure 16 shows a conceptual diagram of these seven stages. The only differences between the three options considered is the sixth and the fifth stage. Fuel extraction, its processing and the infrastructure required is different for the natural gas, the biogas and the hydrogen. Furthermore, operating the hydrogen differs from biogas and natural operation as there is not fuel reforming stage.

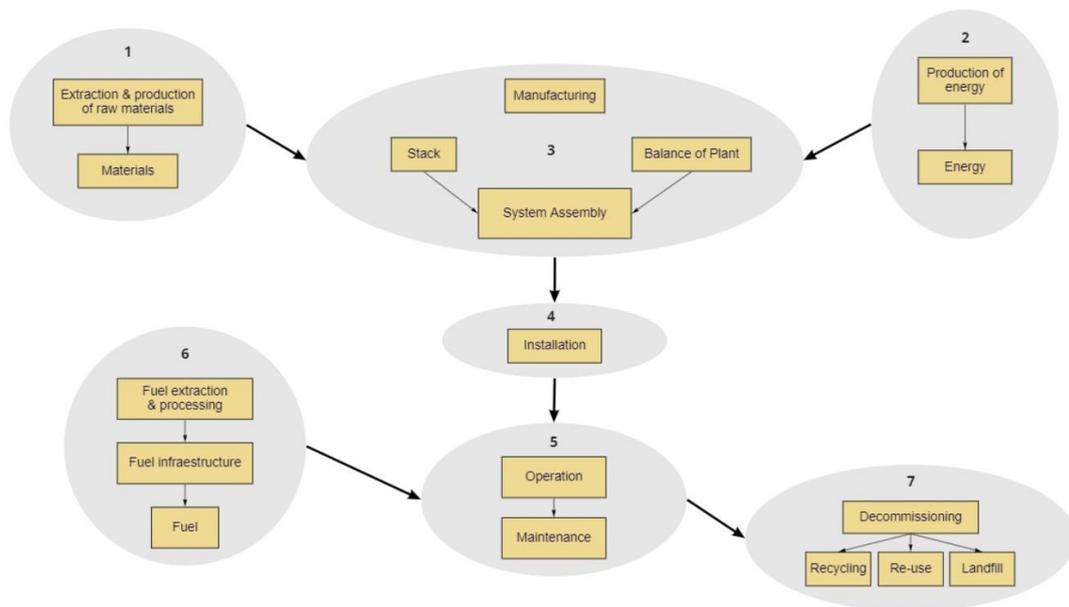


Figure 16. Concept diagram of a fuel cell system's life cycle divided in seven stages. Based on Karakhoussis et al. (2001)

Primary data is collected directly from the manufacturers or direct measurements for the foreground processes: the stack parts manufacture, balance of plant composition, SOFC operation and biogas cleaning. Therefore, the remaining processes belong to the background: raw materials extraction and production, energy generation, decommissioning and fuel processing for natural

gas and hydrogen. Secondary data from databases as EcoInvent 3.7 (2020) will be used for the background processes.

3.2.3.2. *Flowcharts*

A flow chart of the whole system assessed including the three different alternatives compared can be seen in Figure 17.

Bold boxes show the processes that are modelled with primary data. The data regarding the parts manufactured for the SOFC stack is provided by Solid Power. SOFC operation input data is taken from measurements in the test-bed facility in Luleå. Boden biogas facility also provided data regarding the gas composition and its cleaning treatment.

Fuel processing of natural gas includes its exploration, production, and processing, also feeding the produced gas into the pipeline to transport it to the country where it is consumed. Leakages of production and processing are included in the system boundaries as well. It is also considered the transport needed to export Russian and Algerian natural gas to Italy. Losses during seasonal storage are considered.

Biogas manufactured from food waste includes the operation of the plant: reception and weighing of the biowaste, shredding, pasteurization, anaerobic digestion under thermophile conditions, and gas treatment to purify biogas into biomethane. Except for the gas treatment, all the processes are modelled with secondary data from EcoInvent.

Lastly, regarding using green hydrogen as fuel, it is included the Anode Electrolyte (AE) manufacture, the water required for the electrolysis and the energy generated from Italian energy grid.

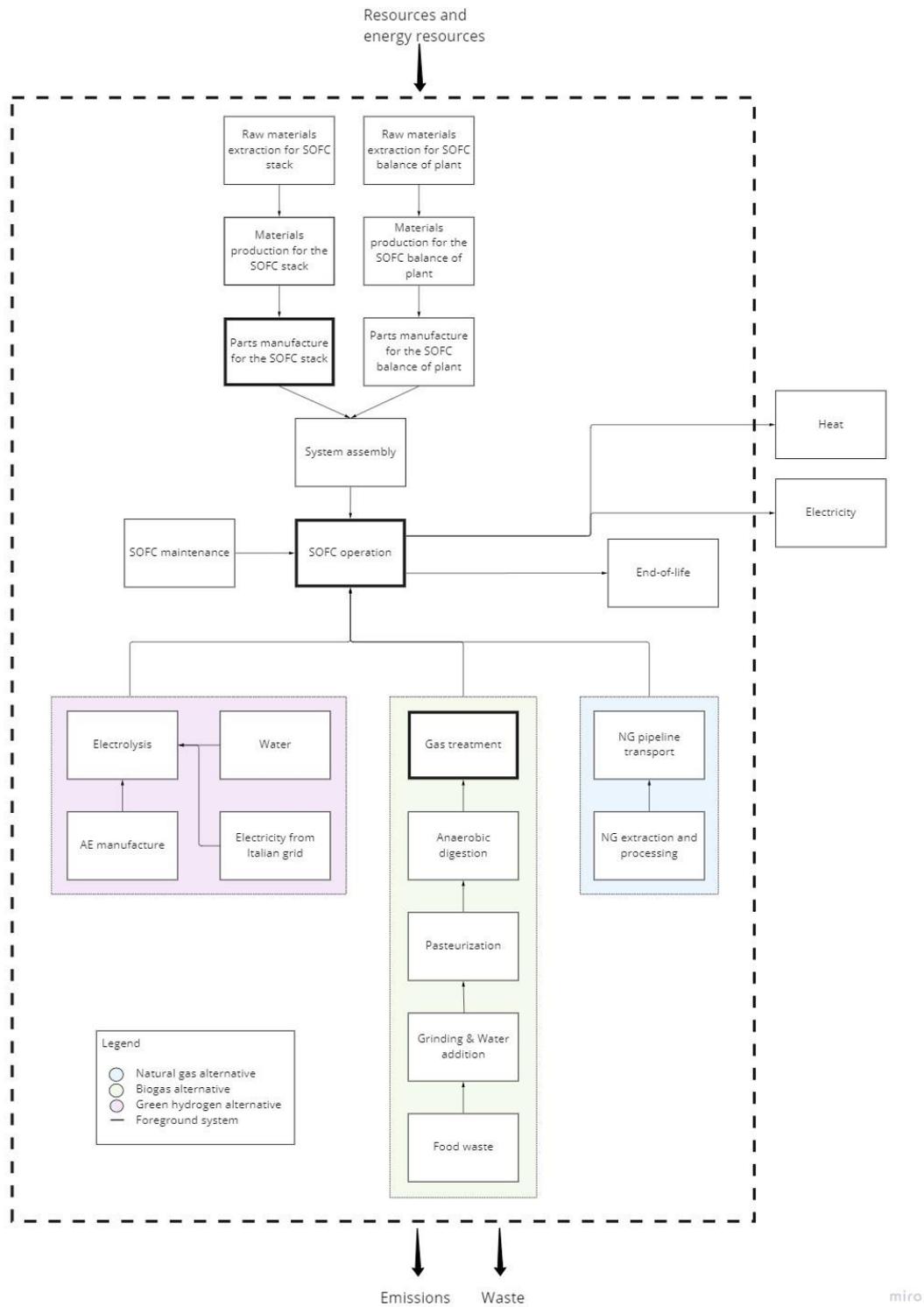


Figure 17. Flow chart of the system assessed

Regarding manufacturing of the SOFC, Figure 7 that was previously presented, shows the processes involved (stage 3 of the concept diagram showed before), including the stack, the balance of plant and its assembly. Each SOFC manufacturer follows different steps and uses different materials and proportions. The scheme provided in this work combines information from communications with Solid Power and data from literature (Al-khori et al, 2021) to complete missing gaps.

3.2.3.3. *Geographical area*

SOFC stacks are manufactured in Italy. Hence, the energy mix of this country should be used to model stack parts. On the other hand, balance of plant parts are assumed to be manufactured in Germany as this is the country where the assembly of the fuel cells from Solid Power takes place.

Regarding the operation, natural gas alternative is modelled in Italy as this is the location where E2P2 project demo site will be implemented. Regarding the biogas alternative, it is modelled for Sweden as this fuel is locally produced in Norrbotten län and the SOFC operation in the WEDISTRIC project, takes place in RISE ICE testbed. Lastly, hydrogen alternative is modelled for Italy as E2P2 project considers using a mix of natural gas and hydrogen as alternative to power the fuel cell.

3.2.3.4. *Time horizon*

To account for the environmental impacts of the different alternatives, the impact of using fuel cells for data center is assessed making use of present data.

3.2.3.5. *Boundaries related to production capital*

Capital goods are used to produce the product studied. Guidelines recommend for accounting LCAs to be as complete as possible, therefore these types of studies should include production or maintenance of capital goods (Tillman et al, 1994). However, for reasons of feasibility this is not included as it would be needed to collect more data. Therefore, the cut-off criterion used is resource related: some parts of the life cycle are excluded due to lack of time and data.

Construction and maintenance of the biogas facility as well as gas pipelines are not part of this LCA. Neither maintenance of the SOFC stack is included.

3.2.3.6. *Boundaries in relation to other products' life cycles*

When performing LCAs it is common to observe several products sharing the same processes. When the environmental load of those products must be expressed in relation to only one product, an allocation problem arises (Baumann et al, 2011). Regarding the fuel cell system, its operation results in multi-output products: electricity and heat. The allocation problem can be phrased as: "How much of the resource consumption and emissions of the process is associated with producing electricity, and how much with the excess heat?". However, as there is no use of the wasted heat at the moment, this output product is considered as waste and all the impact relies on electricity production.

Processes modelled with EcoInvent 3.7 use the system model "Allocation, cut-off by classification". This is based on the recycled content. In this system wastes are responsibility of the producer (commonly known as the "polluter pays" principle). Recyclable products use is incentivised as they are available burden free (cut-off). (EcoInvent, 2022)

3.3. Limitations and assumptions

To be able to build a model of the systems analysed it was necessary to make several simplifications and assumptions listed on the following lines. These are necessary to take into consideration when results are presented and discussed.

- Transportation impact of the SOFC stack and balance of plant is not included. Raw materials transport is included within the processes modelled using EcoInvent.
- Thermal heat produced is considered as waste.
- Energy required for the manufacture of each balance of plant part is not included due to lack of data regarding the magnitude as well as the country of origin.

- According to Lee et al. (2015), material losses during manufacture can be assumed as an extra 10% of material inputs. This assumption was used for the model: balance of plant primary data from Solid Power was increased by 10%.
- The model of biogas production is based on using biowaste as raw material instead of only food waste and WWTP sludge. Not only does it include food and kitchen waste but also biodegradable garden and park waste, as well as forestry or agricultural residues and manure. It does not include sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood.
- It is not considered recycling or any post-use of the digestate originated in the biogas plant.
- Efficiency of the FC decreases with time and thermal cycles. For this study it was assumed that the efficiency keeps constant during the lifespan of the SOFC.
- Gas leakages during the start-up of the SOFC are neglected.

3.3.1. Data sources and quality requirements

Data collected in the inventory is mainly taken from the EcoInvent 3.7 database, information provided by the fuel cell manufacturers as well as direct measurements from RISE ICE data center testbed. A model is done using the SimaPro software which can be later updated with new data and integrated in other project's LCA.

4. Inventory Analysis

In this section it is presented the data gathered for the model and the calculation procedures needed to relate it to the functional unit.

4.1. Calculation methodology

Data is gathered from several sources, so it is obtained in reference to different units. Therefore, it is important to relate all the information acquired to the functional unit selected for this assessment (kWh of electricity produced by the SOFC). Scientific papers used to model the material system provide the data referred to unit of power produced by the FC. To convert power to electrical energy supplied, the following calculation procedure is used.

First, the energy (E_t) provided during one year of operation (t) is calculated. This is done using Equation 5, where 1.5 is the electrical power of the SOFC (Solid Power).

$$E_t = 8760 \frac{h}{y} \cdot 1.5 \text{ kW} = 13140 \text{ kWh} \quad \text{Equation 5}$$

Afterwards, the inventory data provided per SOFC unit is multiplied times the electrical power of the SOFC and divided by the electrical energy provided (E_t) times the number of years of life span of the component.

$$\text{Mass per unit of electrical energy} = \frac{m_{SOFC} [\text{kg}]}{13140 [\text{kWh}/y] \cdot t_{span} [y]} \quad \text{Equation 6}$$

From communications with the manufacturer, it is assumed that the stack life span is 40000 hours (4.57 years) and the balance of plant 20 years.

4.2. Mass and energy balances

Table 4 collects useful data necessary for the calculation of energy balances to obtain the fuel consumption for each alternative evaluated.

Table 4. Energy specifications of the FC and heat value of the fuels

Specification	Magnitude	Source
Electrical power	1.5 kW	Solid Power
Thermal power	0.85 kW	Solid Power
Electrical efficiency	55%	Solid Power
Thermal efficiency	40%	Solid Power
Overall efficiency	85%	Solid Power
LHV biogas	13.5 kWh/kg	Boden Biogas
LHV NG	14.5 kWh/kg	Engineeringtoolbox (n.d.)
LHV H ₂	33.3 kWh/kg	Engineeringtoolbox (n.d.)

The total energy required for 1 year of operation of the SOFC using natural gas, biogas or hydrogen is obtained calculating the total energy output (electricity and heat) for one year and dividing this value by the overall efficiency (η) and the low heating value of each fuel (Equation 7). Dividing the value obtained by the electrical output during one year of operation, the normalized value of fuel input is obtained (Equation 8).

$$\text{Fuel input 1 year of operation (kg)} = \frac{(1.5 [kW_{el}] + 0.85 [kW_{the}]) \cdot 8760 \left[\frac{h}{year}\right]}{\eta \cdot LHV \left[\frac{kWh}{kg}\right]} \quad \text{Equation 7}$$

$$Fuel\ per\ kWh_{el}\ (kg) = \frac{Fuel\ input\ 1\ year\ of\ operation\ [kg]^1}{13140\ [\frac{kWh}{year}]} \quad \text{Equation 8}$$

The total fuel required to produce 1 kWh of electricity using hydrogen is calculated assuming that the SOFC drops its efficiency by 5% (information coming from communications with Solid Power).

Results obtained for each alternative are shown in Table 5. As it is reasonable, the higher heating value of the fuel, the lower fuel necessary to obtain a kWh of electricity output from the SOFC.

Table 5. Fuel consumption for each alternative

	1 year	Normalized
Biogas requirements	1779 kg	0.14 kg/kWh _{el}
NG requirements	1657 kg	0.13 kg/kWh _{el}
H ₂ requirements	765 kg	0.06 kg/kWh _{el}

4.3. Manufacture phase

4.3.1. The SOFC stack

In the following lines it is presented the inventory of the fuel cell stack. This includes a chemical inventory list as well as energy consumption for the manufacturing of parts.

Table 6 includes the net weight of each stack component.

Table 6. Stack parts weight

Item	Net weight of the cell component in the stack (g/SOFC)	Normalized values (g/kWh_{el})	Source
Electrolyte	14	2.33E-04	Solid Power
Cathode	50	8.33E-04	Solid Power
Anode	1260	2.10E-02	Solid Power
Interconnect	30000	5.00E-01	Solid Power
Casing	1323	2.21E-02	Lee et al (2015)
Insulation	304.5	5.08E-03	Lee et al (2015)
Total	32951.5	5.49E-01	

Stack chemical inventory list

Materials required to manufacture the anode, the electrolyte, the cathode and the interconnect, the casing and the insulation, are presented in Table 7, Table 8, Table 9 and Table 10, respectively.

¹ For the hydrogen alternative it is required to increase this value 5% to account for the drop of the SOFC efficiency.

Table 7. Anode chemical inventory list

Item	Actual material inputs including losses (g/SOFC)	Source	EcoInvent
Ni based Y2O3 (ceramic powder)	520	Solid Power	70% Nickel; 30% Aluminum oxide (Lee et al, 2015)
Methyl methacrylate (binder)	630	Solid Power	Methyl methacrylate (MMA)/RER
Water (solvent)	250	Solid power	Tap water (Europe without Switzerland)

Table 8. Electrolyte chemical inventory list

Item	Actual material inputs including losses (g/SOFC)	Source	EcoInvent
Y2O3 stabilized with ZrO2 (ceramic powder)	8.4	Solid Power	Zirconium Oxide (AU) production
Methyl methacrylate (binder)	6.3	Solid Power	Methyl methacrylate (RER) production
Water (solvent)	3	Solid Power	Tap water (Europe without Switzerland)

Table 9. Cathode chemical inventory list

Item	Actual material inputs including losses (g/SOFC)	Source	EcoInvent
LSCF also known as (La, Sr) (Co, Fe)O ₃ (ceramic powder)	39	Solid Power	Lanthanum oxide (RoW) rare earth oxides production
Ethylcellulose (cathode binder)	0.42	Solid Power	Carboxymethyl cellulose
Terpineol (cathode solvent)	14	Solid Power	Ethanol, without water, in 99.7% solution state

Table 10. Other parts chemical inventory list

Item	Actual material inputs including losses (g/SOFC)	Source	EcoInvent
SS (interconnect)	30000	SolidPower	Steel, chromium steel 18/8
SS (casing)	1323	(Lee et al, 2015)	Steel, chromium steel 18/8
Glass ceramic (insulation)	304.5	(Lee et al, 2015)	Glass wool mat (ROW) production

Energy consumed by manufacturing process

Table 11 provides with the data regarding the energy consumed during the manufacturing process of the stack parts following the process previously presented in Figure 7.

Table 11. Energy requirements for the SOFC stack manufacture

Process	Energy input (MJ/kW) ²	Source	EcoInvent
Ball milling (electrolyte)	0.95	Karakoussi et al (2001)	
Tape casting (electrolyte)	0.07	Al-Khori et al (2021)	
Drying (electrolyte)	1.71	Al-Khori et al (2021)	
Sintering (electrolyte)	10.53	Al-Khori et al (2021)	
Total	13.26		Electricity, low voltage (IT) market for
Ink preparation (anode)	0.15	Al-Khori et al (2021)	
Screen printing (electrolyte+anode)	0.13	Al-Khori et al (2021)	
Drying (electrolyte+anode)	1.71	Al-Khori et al (2021)	
Sintering (electrolyte+anode)	8.6	Karakoussi et al (2001)	
Total	10.59		Electricity, low voltage (IT) market for
Slurry preparation (cathode)	0.4	Al-Khori et al (2021)	
Screen printing (electrolyte+cathode+anode)	0.13	Al-Khori et al (2021)	
Drying (electrolyte+cathode+anode)	1.71	Al-Khori et al (2021)	
Co-sintering (electrolyte+cathode+anode)	8.6	Al-Khori et al (2021)	
Total	10.84		Electricity, low voltage (IT) market for
Metal forming (interconnect)	0.43	Al-Khori et al (2021)	Electricity, low voltage (IT) market for

4.3.2. Balance of plant for biogas

The different materials used in the balance of plant components are included in Table 12.

² It is necessary to consider that the SOFC of this study has a power of 1.5 kW. Therefore, all energy values should be multiplied by a factor of 1.5.

Table 12. Balance of plant chemical inventory

Item	Net weight of the component (kg/SOFC) ³	Source	EcoInvent
Pre-reformer	1.7	Solid Power	Iron-nickel-chromium alloy
Heat exchanger	7.3	Solid Power	Iron-nickel-chromium alloy
Burner/Oxidizer	2.31		
Catalyst	9.1 wt%	Karakoussi et al.	Nickel, 99.5%
Box	90.9 wt%	Solid Power	Iron-nickel-chromium alloy
Desulphurizer	10.81		
Catalyst	17 wt%	Karakoussi et al.	Zinc oxide
Box	83 wt%	Solid Power	Steel, chromium steel 18/8
Waste heat recovery	1.9	Solid Power	Steel, chromium steel 18/8
Condensate storage	2.4	Solid Power	HDPE
Demin storage	0.9	Solid Power	HDPE
Power system	0.12		
Al-alloy	90.9 wt%		Aluminium alloy, ALLi
Purified silica	1.2 wt%	Lee et al.	Silicon, metallurgical grade
Plastic	6.1 wt%		Polycarbonate
Copper	1.8 wt%		Copper
Case	72	Solid Power	Cold rolled steel
Air and fuel supply system ⁴	30	Karakoussi et al.	Steel, chromium steel 18/8

4.4. Fuel extraction and processing

4.4.1. Natural Gas

Natural gas extraction, processing and import to Italy is modelled using data from EcoInvent database. According to Statista (2022), most of the NG imported in Italy comes from Algeria and Russia.

Table 13. Natural gas requirements (normalized)

Item	Amount	Source	EcoInvent
NG	0.13 kg/kWh	Own calculations (Table 5)	Natural gas, high pressure (IT) imports from RU and import from DZ (ratio 0.55:0.45)

³ To account for losses during the manufacture phase of each component, it is assumed an extra 10% of material inputs. This criterion was used on previous LCAs of SOFC (Lee et al, 2015)

⁴ It includes air blower, air control valves, piping, condensate pump, water safety valves, polish pump and metering pump.

4.4.2. Biogas

Biogas production is modelled using foreground data for the raw gas cleaning (Table 14) and background data for the processing of food waste and its transformation into gas. Clean gas is the biomethane, which is used for running the SOFC. Stripper gas contains all the impurities present in the raw gas produced during anaerobic digestion. The stripper gas is considered as waste, and it is released into the atmosphere. Therefore, using the concentrations provided in Table 15, it is calculated the amount of each component that is released. Results are collected in Table 16.

Table 14. Gas flows in the cleaning process

Item	Amount	Source	EcoInvent
Raw biogas production	150 Sm ³ /h	Boden biogas	Biogas {CH ₄ } treatment of biowaste
Clean gas	92 Sm ³ /h	Own calculation	by anaerobic digestion ⁵
Stripper	75 Sm ³ /h	Own calculation	

Table 15. Primary data of biogas cleaning process emissions (Boden biogas)

Component	Unit	Raw gas	Stripper ⁶	Clean gas
Methane	%-vol	59.5	0.65	96.5
Carbon dioxide	%-vol	38.2	21.3	2.9
Oxygen	%-vol	< 0.1	16.2	0.2
Nitrogen	%-vol	< 0.3	60.6	0.4
Carbon monoxide	%-vol	< 0.1	< 0.1	< 0.1
Hydrogen	%-vol	< 0.1	< 0.1	< 0.1
Water	%-vol	2.2	1.2	
Dioxide content	ppm-vol	140	50	< 1
Density	kg/Sm ³	1.11	1.34	0.72
Lower heating value	MJ/kg	18.1	-	45.7

Table 16. Emissions to the atmosphere during the gas cleaning

Emissions to atmosphere	Density (kg/m ³) ⁷	Amount (kg/h)
Methane (biogenic)	0.67	0.33
Carbon dioxide (biogenic)	1.84	29.43
Oxygen	1.33	16.17
Nitrogen	1.17	52.95
Hydrogen	0.09	0.01
Water	0.8	0.72

4.4.3. Hydrogen

To assess the environmental impact of using hydrogen as an alternative to power SOFC, it was gathered data concerning the materials used to manufacture the anode electrolyte as well as

⁵ EcoInvent model was modified to exclude the construction phase of the facility

⁶ This accounts as emissions to air

⁷ Values taken from Engineeringtoolbox (n.d.)

resource consumption during the electrolysis process. Data included in the model is shown in Table 17.

Table 17. Inventory list for anode electrolyte manufacture and operation

Item	Anode Electrolyte (AE)	Source
Stack lifespan	120000 h	
Electrical consumption	50 kWh/kg H ₂	
Water consumption	10 kg/kg H ₂	(Delpierre et al, 2021)
Steel consumption	10 kg/kW	
KOH consumption	1 g/kg H ₂	
Nickel consumption	0.2 kg/kW	

Figure 18 shows the share of the different energy sources in the Italian grid. This must be taken into consideration when discussing the impacts of using electricity from the grid to produce hydrogen by electrolysis. Since more than half of the electricity comes from non-renewable sources, grey hydrogen is produced.

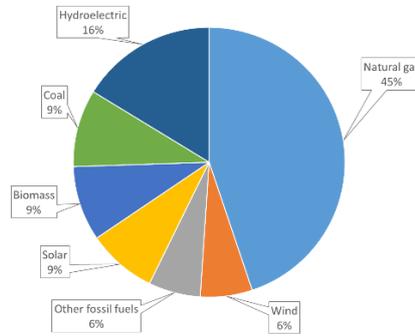


Figure 18. Italy energy mix: 2018 (Statista, 2021)

4.5. SOFC operation with biogas, natural gas, and hydrogen

Table 18 shows the inputs and outputs of the SOFC during its operation. Data used corresponds to when the SOFC reaches steady state (the voltage of cells does not vary with time). Also, it is verified the Principle of Conservation of Mass: the total mass getting in the system is equal to the total mass getting out of the system.

Table 18. Mass balance calculations for the SOFC operating with NG, biogas and hydrogen

Inputs		
Item	Amount ⁸	Source
Water	4.17E-4 kg/s	Solid Power
Air	3.68E-3 kg/s	Solid Power
Fuel		
NG	5.64E-05 kg/s	
Biogas	5.25E-05 kg/s	
H ₂	2.42E-05 kg/s	
Outputs		
Item	Amount	Source
Water	3.13E-4 kg/s	Solid Power
Flue gas	3.78E-3 kg/s	Own calculations ⁹

⁸ Normalized values can be obtained by calculating the requirements for one year and dividing by the electricity produced during that time (13140 kWh).

⁹ Water is consumed as well as produced in the different reactions inside the fuel cell. Calculations were done assuming steady state conditions and mass conservation law.

Emissions in the flue gas were calculated using the stoichiometry of the reactions involved. Further explanations on the procedure followed can be found in Annex I.

Table 19. Flue gas composition

Carbon dioxide emitted	
Natural gas	0.39 kg/kWh _{el}
Biogas	0.36 kg/kWh _{el}

4.5.1. Maintenance

BG-15 SOFC operation needs maintenance of some parts. Specifications recommend replacing parts such as the air and water filters every two years and the desulphurizer between 1 and 3 years. However, because of lack of data, neither the water and air filters nor the desulphurizer were included in the inventory. Therefore, maintenance was not considered in the modelling of the system.

4.6. Decommissioning

As fuel cells are a novel technology, there are not predefined treatments for its end-of-life. Communications with the manufacturer did not provide any relevant data as an external company is responsible for the decommissioning. Hence predefined waste processes were selected for the stack and the BoP.

Table 20. EoL treatment of the SOFC

	EoL treatment	Waste type
Stack	Recycling of steel and iron {GLO}	Stainless steel and alloys
	Incineration of hazardous waste {Europe without Switzerland}	All other parts
BoP	Waste incineration of plastics {RER}	HDPE
	Recycling of steel and iron {GLO}	Stainless steel and alloys
	Incineration of hazardous waste {Europe without Switzerland}	All other parts

5. Impact Assessment

5.1. Manufacture of the stack, the balance of plant, and its end of life

The most relevant contributions to each impact category are described in the following lines and shown in Figure 19.

5.1.1. Stack manufacture and disposal

Results for the stack show that within the climate change category, the highest impact comes from the manufacture of SS 304, specifically, ferronickel production, for the interconnect. This is an energy intensive process and today most of the energy required comes from burning fossil fuels (natural gas and coal), what emits carbon dioxide into the atmosphere.

Regarding respiratory inorganics, the highest impact also arises from SS 304 production. This is linked to the energy required for the converter manufacture, specifically the chemical process that turns raw iron into steel.

Energy requirements to produce ferronickel for the interconnect and nickel mining for the anode are responsible for most of the impact in the acidification category.

Looking into water scarcity, the highest impact comes from the anode manufacture. Particularly, obtaining the methyl methacrylate using the acetone cyanohydrin route. Also, there is some contribution to this impact from ferrochromium and ferronickel production for the interconnect.

Resource use of energy carriers is mainly due to the interconnect material production. Ferronickel production is linked to a high consumption of electricity and heat. Use of coal and natural gas account for most of this impact.

Lastly, Nickel, Zinc and Lime operation as well as ferronickel and chromite ore concentrate production are the main responsible for the mineral and metal resource use impact category. These processes are required to manufacture the steel used for the interconnect.

Characterized impact results (stack)

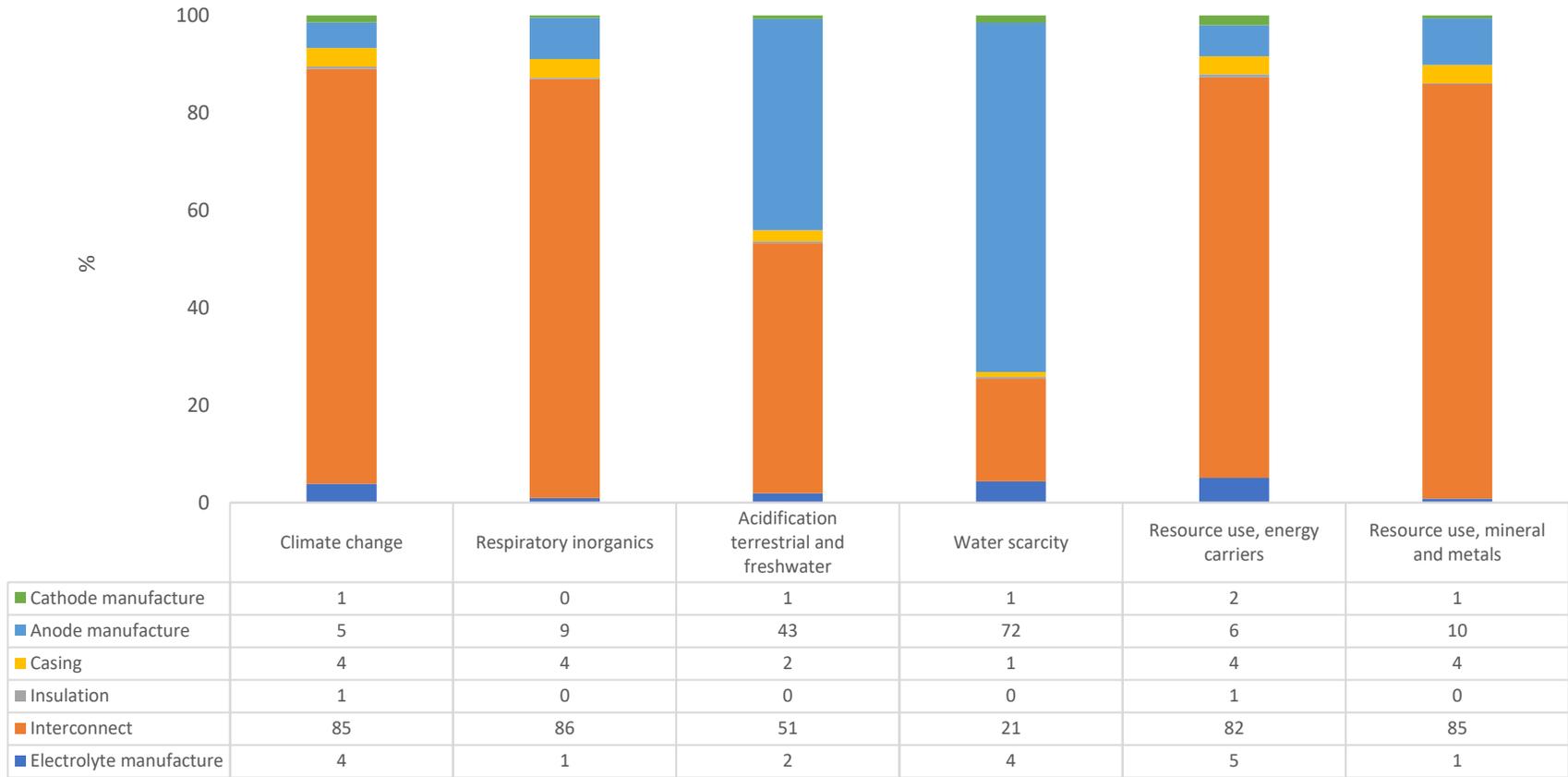


Figure 19. Relative contribution of different parts of the stack manufacturing to the selected impact categories

Taking into consideration the disposal phase of the stack, as it can be visualized in Figure 20, the most relevant contribution comes from the climate change category. This is linked to the incineration of hazardous waste as the heat required for the incineration process comes from a coal stove filled with anthracite. This process is also responsible for most of the respiratory inorganics and resource use of energy carrier's categories. Absolute end-of-life impact results for each category are gathered in Table 21.

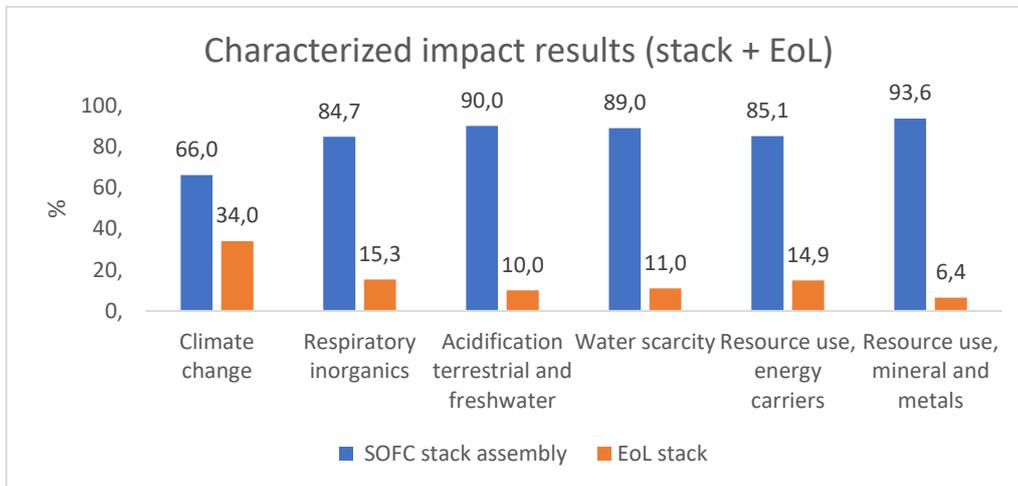


Figure 20. Comparison of the manufacture and disposal impact of the stack.

5.1.2. Balance of plant manufacture and disposal

Moving on to the balance of plant, as it was previously described, this part consists of air and fuel supply system, power system, case, demin storage, condensate storage, desulphurizer, burner/oxidizer, heat exchanger and pre-reformer.

The FC case contributes the most to the climate change impact, followed by the air and fuel supply system (see Figure 21). This is connected to the manufacture of steel cold rolled coil and steel production in the converter.

Respiratory inorganics impact is mainly due to the air and fuel supply system. This is linked to the energy required for manufacturing chromium steel since it comes from coal and there is a high impact of mining activities. Manufacturing iron-nickel-chromium alloy also has a considerable impact because of nickel mining.

Looking into acidification, nickel mining (which is in the sulfidic ore) as well as platinum group metal mining (nickel can also be found in ores with high palladium content) has a relevant impact on the production of iron-nickel-chromium alloy.

Water scarcity is mainly affected by mining operation to obtain the nickel from the sulfidic ore which is needed for the heat exchanger. Steel cold rolled coil of the case manufacture also impacts this category as well as the electricity required for ferronickel production. This is necessary to manufacture the air and fuel supply system and has the highest process contribution impact.

Regarding energy carriers resource use, these are mainly used for the steel manufacture in the converter. This is required for the air and fuel supply system. Steel cold rolled coil of the case also has high energy demand.

When it comes to mineral and metals use, the power system has one of the largest impacts due to the need of zinc. The fuel and air supply system also has high requirements of minerals and metals due to chromite ore concentrate production. Lastly, nickel mine operation contributes considerably to this impact category.

Characterized impact results (BoP)

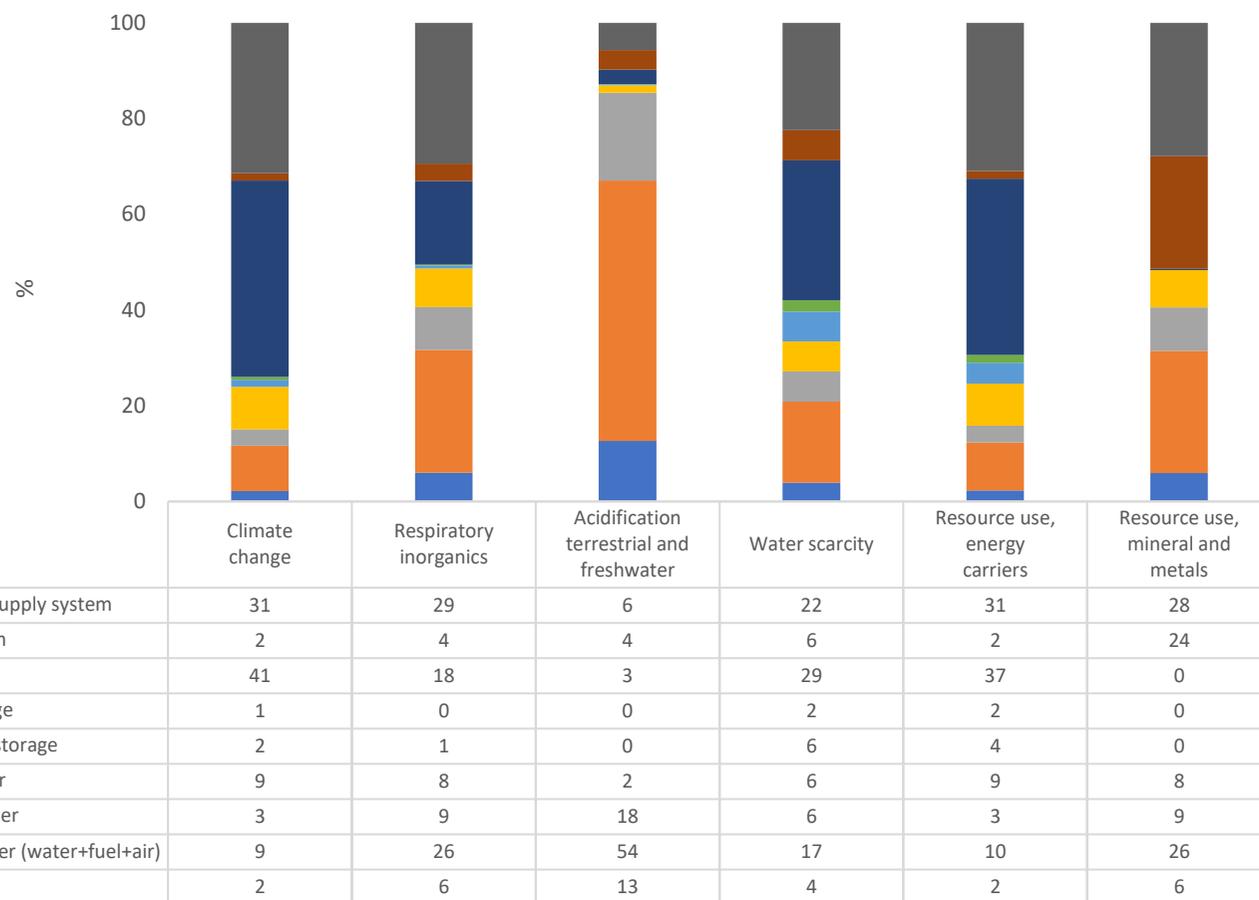


Figure 21. Relative contribution of different parts of the balance of plant manufacturing to the selected impact categories

Taking into consideration the disposal phase of the balance of plant (see Figure 22), the most relevant contributions come from the climate change category as well as water scarcity. Climate change impact is linked to the incineration of hazardous waste as the heat required for the incineration process comes from a coal stove filled with anthracite. Also, there is an intense water use in the chlor-alkali electrolysis cells, that are used in the production of sodium hydroxide. This chemical compound is used in a moderate thermal treatment to stabilize lead in fly ash incineration (Gong et al, 2017).

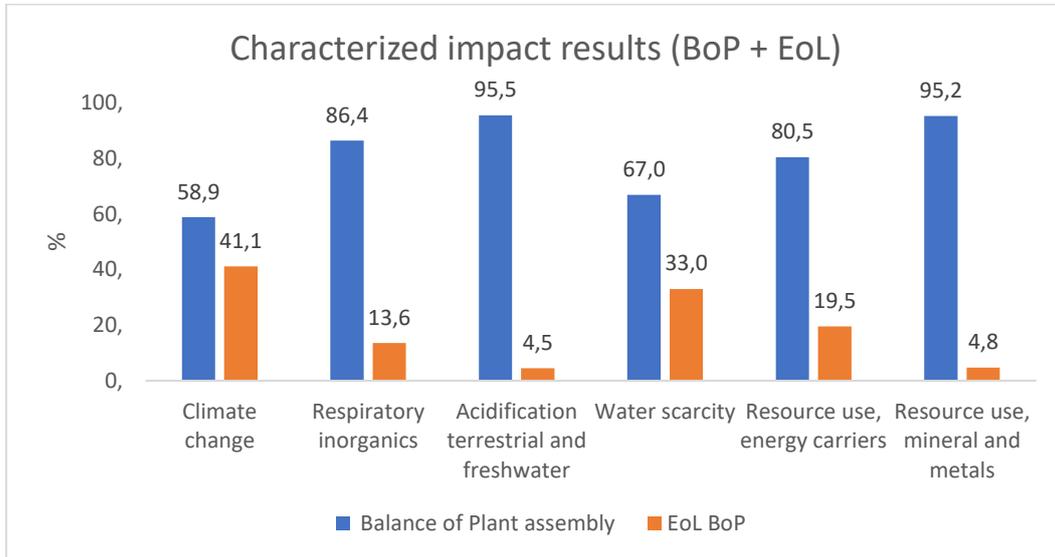


Figure 22. Comparison of the manufacture and disposal impact of the balance of plant.

Results for each impact category are gathered in Table 21. Stack manufacture has a higher impact on climate change, respiratory inorganics, water scarcity and resource use of energy carriers and minerals and metals than the balance of plant. Concerning the disposal phase, there is a similar impact for both parts of the SOFC.

Table 21. Life cycle impact results for the stack and the balance of plant referred to the functional unit (kWh_{el})

Impact category	Unit	Stack manufacture	Stack EoL	BoP manufacture	BoP EoL
Climate change	kg CO ₂ eq	2.96E-03	1.52E-03	1.81E-03	1.26E-03
Respiratory inorganics	disease inc.	2.60E-10	4.69E-11	1.71E-10	2.69E-11
Acidification terrestrial and freshwater	mol H ⁺ eq	3.16E-05	3.52E-06	6.47E-05	3.02E-06
Water scarcity	m ³ deprivation	1.51E-03	1.88E-04	3.20E-04	1.58E-04
Resource use, energy carriers	MJ	3.26E-02	5.72E-03	1.95E-02	4.73E-03
Resource use, mineral and metals	kg Sb eq	1.09E-07	7.43E-09	7.47E-08	3.73E-09

5.2. Comparison of the three fuel alternatives analysed

Impact results of manufacturing the fuel alternatives as well as operating the SOFC, are analysed in this section. Quantitative results are collected in Table 22. Figures 23 to 28 visually show the impact for each category when using natural gas, biogas and hydrogen to feed the fuel cell.

Table 22. Life cycle impact results of the manufacture and fuel production and operation of the SOFC for each alternative referred to the functional unit (kWh_{el})

Impact category	Units	Stack	BoP	NG	BG	H2 (from IT grid)
Climate change	kg CO ₂ eq	4.48E-03	3.07E-03	5.06E-01	3.17E-01	1.27
Respiratory inorganics	disease inc.	3.07E-10	1.98E-10	9.65E-10	1.43E-09	2.42E-08
Acidification terrestrial and freshwater	mol H ⁺ eq	3.51E-05	6.78E-05	3.94E-04	3.94E-04	6.51E-03
Water scarcity	m ³ deprivation	1.70E-03	4.79E-04	4.14E-02	4.38E-02	7.93E-01
Resource use, energy carriers	MJ	3.84E-02	2.42E-02	6.03	2.37E-01	18.70
Resource use, mineral and metals	kg Sb eq	1.16E-07	7.84E-08	9.00E-08	5.57E-08	1.38E-06

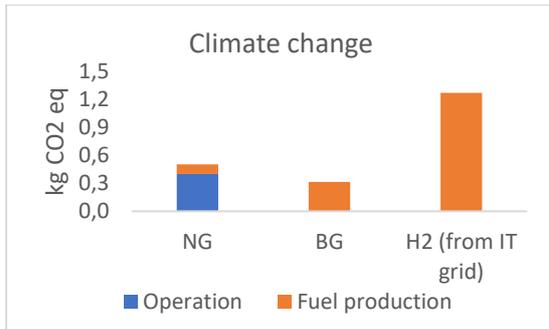


Figure 23. Climate change impact of the alternatives analysed

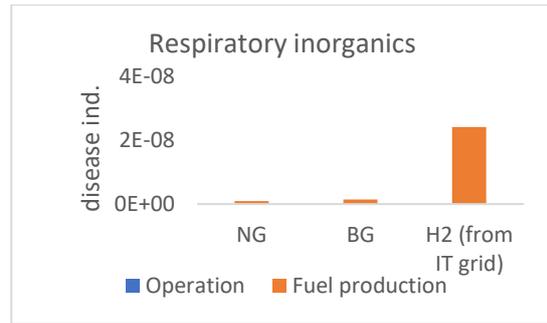


Figure 24. Respiratory inorganics impact of the alternatives analysed

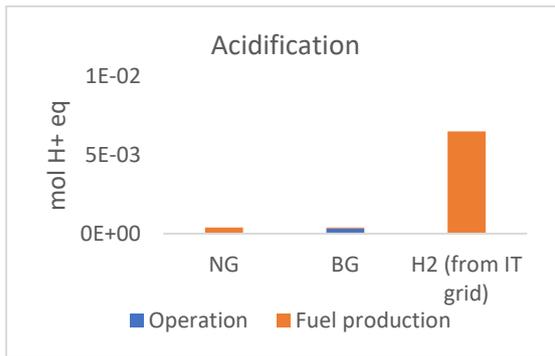


Figure 25. Acidification impact of the alternatives analysed

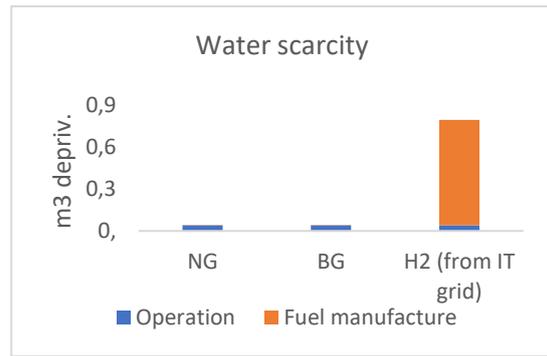


Figure 26. Water scarcity impact of the alternatives analysed

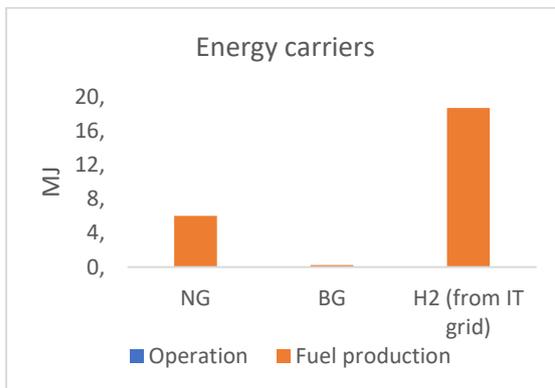


Figure 27. Resource use – energy carriers, impact of the alternatives analysed

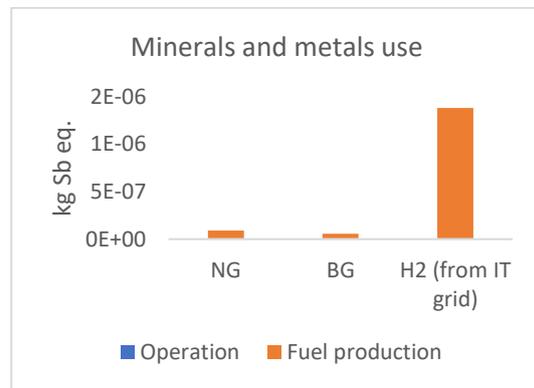


Figure 28. Resource use – mineral and metals, impact of the alternatives analysed

Results for each of the alternatives analysed, show that biogas has the lowest contribution (0.32 kg CO₂eq/kWh_{el}) to climate change impact contribution, followed by natural gas (0.5 kg CO₂eq/kWh_{el}) and hydrogen options (1.27 kg CO₂eq/kWh_{el}). Hydrogen and biogas impact comes from its production. Most of natural gas climate change impact arises from the fuel cell operational phase, where CO₂ is produced in the water-shift reaction as well as in the afterburner to consume the unreacted methane and the CO₂ produced is directly emitted to the atmosphere. The balance of plant (3.07E-0.3 kg CO₂eq/kWh_{el}) and stack manufacture and disposal (4.48E-0.3 CO₂eq/kWh_{el}) have a negligible contribution to global warming category compared to the manufacture of the fuel and operating the fuel cell. Overall, climate change impact shows that hydrogen produced using energy from the Italian grid has the highest global warming emissions. The reason behind this relies on the fact that electricity in Italy mainly comes from natural gas and water electrolysis is an energy intense process.

Hydrogen alternative is the main contributor to particulate matter ($2.42\text{E-}08$ disease inc. / KWh_{el}). This is mostly connected to electricity production in the Italian energy mix (use of coal, oil, biogas gas engine, natural gas, and wood chips). Biogas impact ($1.43\text{E-}09$ disease inc. / KWh_{el}) arises from the machine operation in the plant, which was modelled running with diesel. Natural gas has the lowest contribution to this category ($9.64\text{E-}10$). All the impact for this category comes from fuel manufacturing.

Looking into acidification, most of the impact also arises from the hydrogen ($6.51\text{E-}03$ mol $\text{H}^+\text{eq/kWh}_{\text{el}}$), specifically due to the energy mix of the Italian grid. Electricity produced from hard coal and heat and power co-generation using oil are the processes responsible for this impact. Natural gas ($3.94\text{E-}4$) and biogas ($6.73\text{E-}5$) impact is negligible compared to hydrogen.

Continuing the trend, results for water scarcity category show hydrogen as the alternative with the highest impact (0.79 m^3 depriv.). Operation of the fuel cell consumes and produces water. As it consumes more water than it is produced, its operation has a small contribution to water deprivation. Natural gas and biogas almost do not use water during its fuel manufacture whereas producing hydrogen by using electricity from the Italian grid leads to 0.75 m^3 depriv./ kWh_{el} . What explains these results is the use of hydroelectric power to produce 16.3% of this energy (see Figure 18).

Lastly, regarding energy carriers resource use: hydrogen has a high contribution to this category due to the energy required for the electrolysis (18.7 $\text{MJ/KWh}_{\text{el}}$). Most of it comes from non-renewable sources such as coal, oil or natural gas. Using natural gas as fuel also has a meaningful impact because of its fossil fuel origin. This alternative requires 6 $\text{MJ/KWh}_{\text{el}}$ produced.

In the same way, hydrogen is responsible for most of the impact of minerals and metal use ($1.38\text{E-}6$ $\text{kg Sb eq/KWh}_{\text{el}}$). This is linked to the use of different metals in the technologies to produce all the energy required for the electrolysis as well as the energy transmission network construction, which uses materials such as zinc or clinker. Natural gas and biogas impact on mineral and metal resource use is considerably less ($9\text{E-}0.8$ and $7.6\text{E-}0.8$ $\text{Sb eq/KWh}_{\text{el}}$). It should be highlighted that the stack and balance of plant manufacture have a higher impact on this category than biogas and natural gas production and operation.

The impacts of each alternative compared with the manufacture of the SOFC are collected in the figure below (Figure 29). When looking to the hydrogen alternative, fuel manufacture is responsible for almost its total environmental impact. If the other two alternatives are compared, it is possible to see very similar trends: climate change impact is mostly influenced by operating the SOFC and fuel production; respiratory inorganics as well as acidification and energy carriers' impact is caused by producing the fuel. Water scarcity impact arises from the operation phase. Lastly, the balance of plant and stack manufacture are responsible for most of the metals and minerals resource depletion.

Characterization results for the SOFC LCA

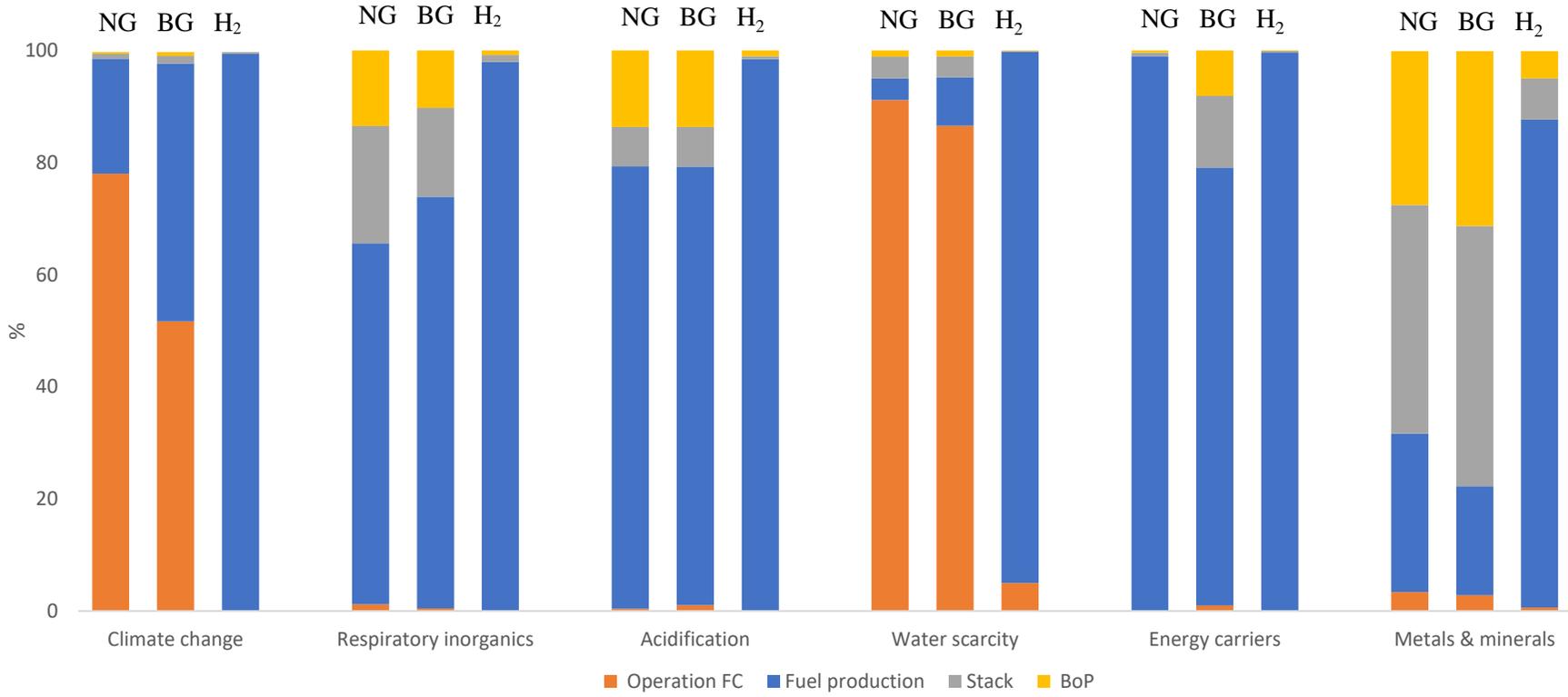


Figure 29. Characterization results for the SOFC life cycle

5.3. Sensitivity analysis

5.3.1. Energy source to produce hydrogen by electrolysis

Hydrogen production is energy intense. Therefore, the sensitivity of the impacts when using different energy sources for manufacturing the hydrogen fed to the SOFC is analysed. Using energy coming from the Italian grid was considered the business-as-usual case (bau). As renewable energies are seen as a promising alternative to produce hydrogen when there is an excess of energy production, together with the possibility of enabling energy storage as hydrogen, comparing the impact of using different green energies is found relevant. The four options included in this comparison are energy from the Italian grid, hydropower energy, solar power as well as wind power. The impact of each alternative is shown in Table 23.

To make a fair comparison with the biogas and natural gas alternatives, not only is the production phase included, but also the operation of the SOFC. As it was explained in the results section, the operational phase using natural gas and biogas has a significant impact whereas for hydrogen is almost negligible in most of the categories. Therefore, the operation of the SOFC to assess the impact of using different energy sources is taken into consideration for this analysis.

Table 23. Impact of different energy sources for hydrogen production and operation referred to the functional unit (kWh_{el})

Impact category	Unit	Italian energy mix (bau)	Hydropower	Wind energy	Solar energy
Climate change	kg CO ₂ eq	1.27	0.02	0.05	0.21
Respiratory inorganics	disease inc.	2.42E-08	1.43E-09	4.31E-09	1.39E-08
Acidification terrestrial and freshwater	mol H ⁺ eq	6.51E-03	7.73E-05	3.35E-04	1.39E-03
Water scarcity	m ³ depriv.	7.93E-01	3.96	0.05	0.21
Resource use, energy carriers	MJ	18.70	0.16	0.58	2.54
Resource use, mineral and metals	kg Sb eq	1.38E-06	1.54E-07	1.41E-06	3.41E-05

Figure 30 shows that using any of the renewable energy alternatives carbon dioxide equivalent emissions could be reduced. Since part of the Italian grid energy is produced by burning fossil fuels, this affects global warming. Also, natural gas leaks may occur during its extraction and transport, impacting this category. Fossil fuels burning is linked to the release of respiratory inorganics to the atmosphere. Therefore, the same tendency as for climate change category can be seen in Figure 31. However, it is relevant to highlight that solar energy has a considerably higher impact than hydropower or wind power. Photovoltaic panel production for solar panels technology is the main responsible of releasing particulate matter into the air.

In addition, Italian energy mix stands out when looking into the acidification category (Figure 32). Electricity production using hard coal produces H⁺ ions responsible for terrestrial and freshwater acidification. Photovoltaic plant construction also significantly contributes to this category when it is compared to hydropower or wind energy.

Since hydropower energy needs an important amount of water, this energy source impact surpasses the three other options to manufacture hydrogen. This can be seen in Figure 33. Also,

the use of hydropower in the Italian grid pinpoints the impact of this alternative on water consumption.

Looking into energy carriers resource use, Figure 34 highlights the impact of Italian energy mix on this category. As more than half of the electricity share in Italy comes from non-renewable energy sources (Figure 18), it is reasonable that this alternative has a high impact as well.

In contrast, when metal and mineral use category is analysed, solar power impact outstands when compared to the other alternatives. This can be visualised in Figure 35. Extraction of raw materials such as gold, silver, copper lead or zinc from the Earth crust needed to build the photovoltaic plant, originates a big impact on this category.

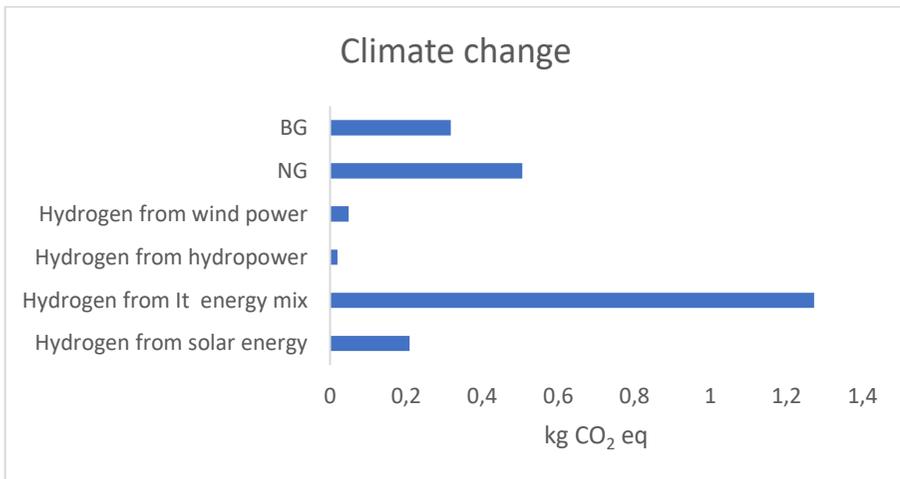


Figure 30. Climate change impact of different energy sources to produce hydrogen

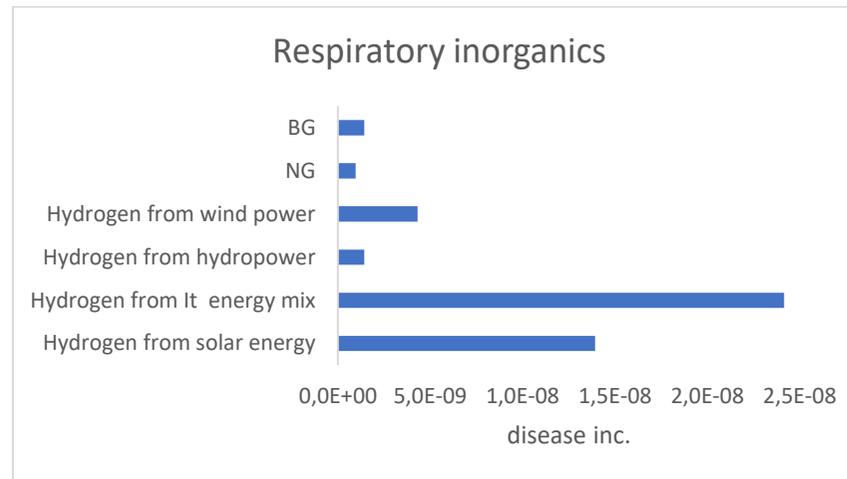


Figure 31. Respiratory inorganics impact of different energy sources to produce hydrogen

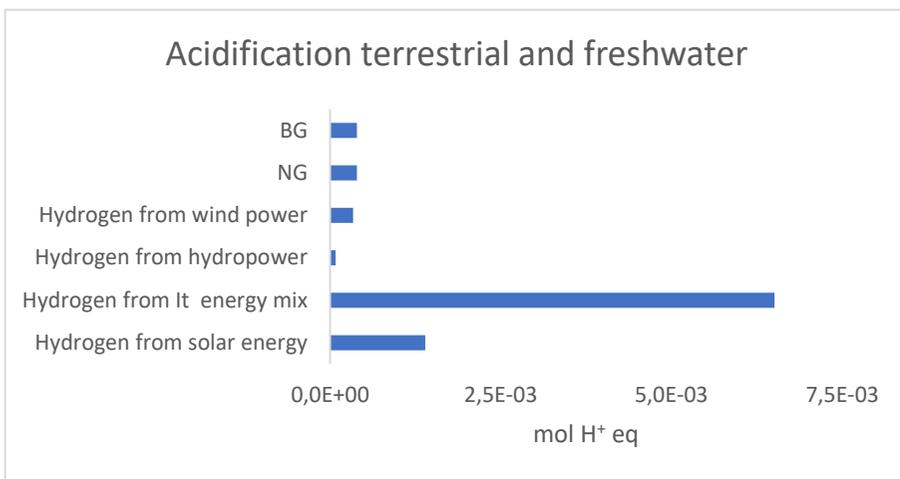


Figure 32. Acidification impact of different energy sources to produce hydrogen

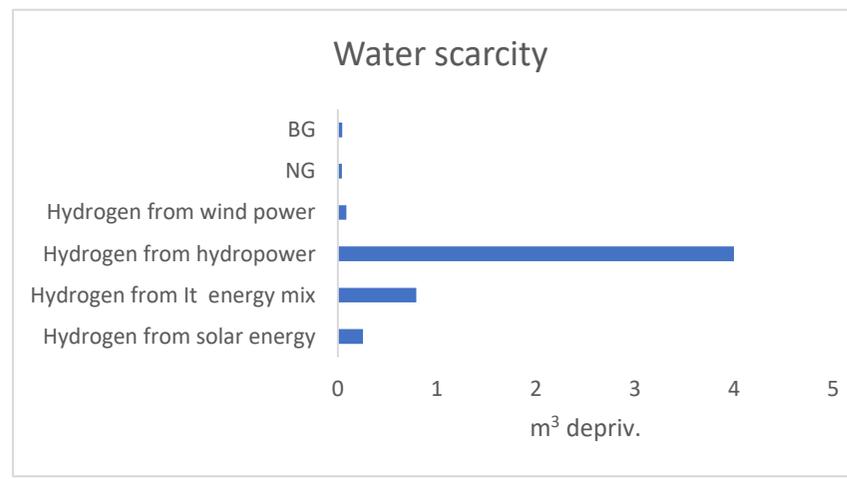


Figure 33. Water scarcity impact of different energy sources to produce hydrogen

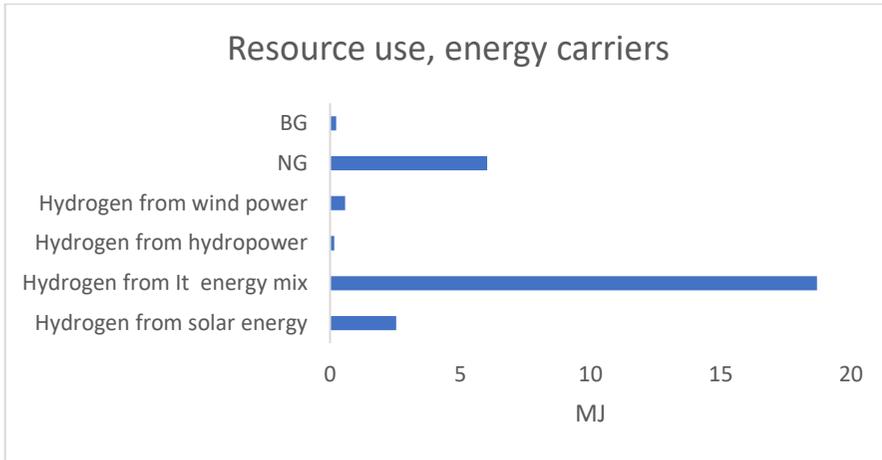


Figure 34. Resource use (energy carriers) impact of different energy sources to produce hydrogen

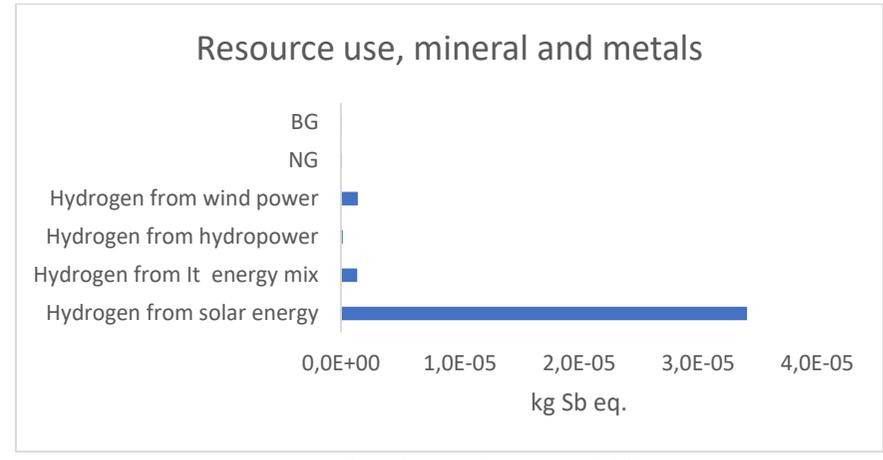


Figure 35. Resource use (metals and minerals) impact of different energy sources to produce hydrogen

5.3.2. Sensitivity to increase the material of the air and fuel supply system

Air and fuel supply system consists of air blower, air control valves, piping, condensate pump, polish and metering pump as well as water safety valves. Inventory data of these parts was taken from literature as since data was provided by the manufacturers. Therefore, analysing how the balance of plant impact will be influenced by increasing the amount of material used for these parts is of interest. The sensitivity of the BoP impact when the mass of steel used in the air and fuel supply system increases by 30%, 50% and 70% is checked. Results are shown in Figure 36.

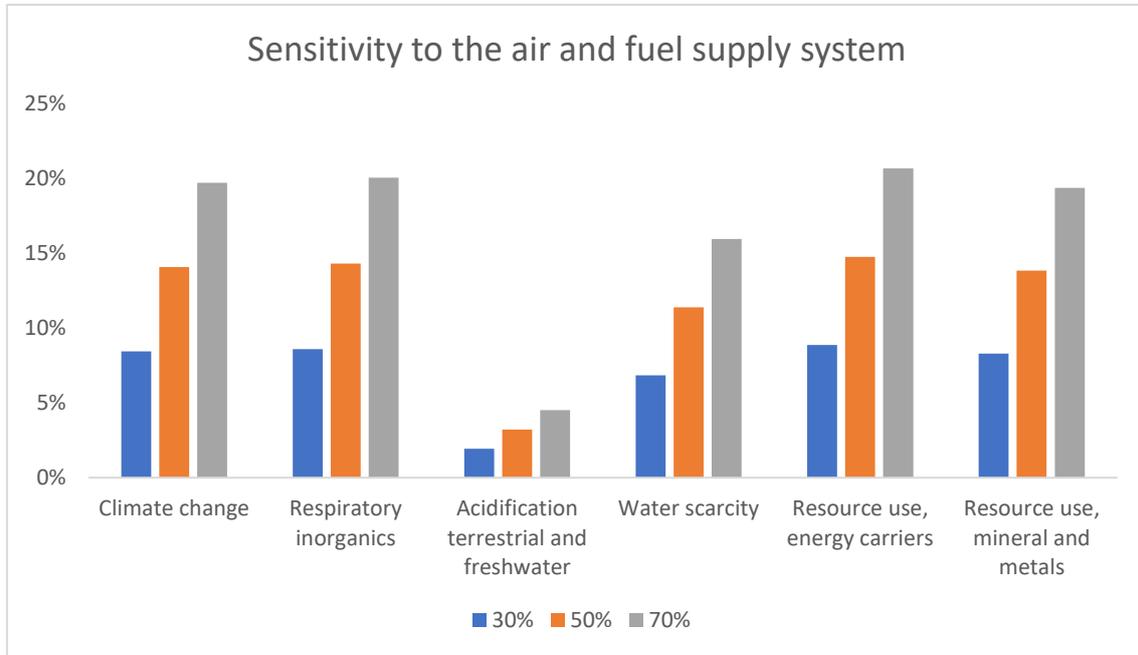


Figure 36. Air and fuel supply system sensitivity analysis

Most of the impact categories will have a notable increase on its environmental burden when rising the mass of steel used for the air and fuel supply system. Only acidification category will be minimally affected. Therefore, it should be pinpointed that the air and fuel supply system parts impact is a rough estimation, and its real value may differ. When increasing the mass of these parts by half, all the impact categories for the balance of plant will rise between 11 to 15% compared to the value assumed for this assessment. Only acidification impact increase will remain almost negligible (3%).

6. Discussion of results and mitigation measures

Results demonstrate that most of the impact comes from manufacturing the fuel and the SOFC operational phase for all the categories considered except from metals and minerals resource use. This coincides with Abdelkareem et al. (2021), who stated that for SOFC commonly the impacts depend on the type of fuel being used as well as how it has been produced. Also, Moretti et al. (2020) brought fuel production phase as a big contributor to the total impact of the system.

Hydrogen production by electrolysis using energy from the Italian energy mix has the highest impact for all the categories included in this assessment. This shows that the energy source used for the electrochemical reaction is critical. Getting a high impact for this alternative was expected since today the Italian energy grid highly relies on fossil fuels. Hence, it was also relevant to analyse hydrogen production via electrolysis using the most likely path now. However, other energy sources were analysed to investigate to what extent it is possible to reduce the environmental burden of this alternative when switching the energy source.

None of the three alternatives included in the sensitivity analysis to produce green hydrogen (hydropower, wind power and solar energy) is found to be ideal. For instance, if there is a high interest on reducing GHG emissions, wind power, hydropower and solar energy would be good alternatives, however solar energy would deeply impact mineral and metals resource use while water scarcity will be very affected when using hydropower. Anyhow, acidification, climate change, energy carriers resource use and respiratory inorganics impact could be considerably reduced when using any of the green energy sources assessed. Thus, increasing the share of these renewable energies in the Italian grid could significantly minimise the impacts previously mentioned. However, being aware of its environmental burdens would also help to make improvements on green technologies.

Comparing the biogas and natural gas alternatives, biogas has a lower climate change and fossil resource use. Natural gas shows better performance for the particulate matter. These results are in line with Rillo et al. (2017) outcome. Oppositely to hydrogen, that has a negligible impact on the operational phase as no burning of the fuel takes place, natural gas and biogas alternatives have a salient impact when they are fed to the SOFC.

Al-Khori et al. (2021) results brought GWP, acidification and particulate matter as critical impacts when operating SOFCs. However, for the present study results show that when operating the SOFC with biogas and NG, the only impact categories affected are water scarcity and climate change. One possible reason behind this discrepancy could be that for the present study flue gas emissions neither were possible to be measured in the demo-site nor found in literature, thus rough estimations regarding its composition were made. This is a critical aspect since the flue gas is directly emitted to the atmosphere and neglected emissions could modify the overall impact, mainly affecting GHG emissions and acidification (since NO_x emissions could be present in the flue gas). Hence, verification with data coming from on-site measurements should be done.

Increasing the fuel cell efficiency or capturing the carbon dioxide emitted could help to reduce the operational phase impact. Using carbon capture technology integrated with SOFC has already been studied by Rillo et al. (2017). Also, a possible measure to decrease water consumption could be recirculating the water produced during the electrochemical reaction to generate electricity instead of sending it to the drainage.

In addition, it was not included the heat produced as a valuable product. Since it is a by-product, but no use is given to it now, it is considered as waste. In case it is used, for instance to contribute to the district heating, allocation could be done for the electricity and the heat produced. Consequently, total impact per kWh of electricity produced would decrease.

During the gas cleaning phase of the biogas as well as natural gas extraction and transport, methane leaks take place. Moreover, there are not fossil carbon dioxide emissions during the operational phase for the biogas alternative. This is connected to the origin of these two energy carriers. Using fossil fuels affects the slow domain of the carbon cycle: carbon that has been locked up in the ground for millions of years is released to the atmosphere. In contrast, bioenergy systems operate within the fast domain: emissions linked to biomass sources return to the atmosphere the carbon captured as the plants grew (IEA, 2020). Hence, even if methane leaks and CO₂ emissions take place for both alternatives, for the biogas alternative they are modelled as biogenic, and their impact is slightly lower (characterization factors for carbon dioxide and methane in the climate change category are 1 and 36.8 respectively for fossil and, 0 and 34 respectively for biogenic origin, according to EF 3.0).

Anyhow, it should be noted that the energy used to operate the anaerobic digestion plant was assumed to come from the Swedish electrical grid. From communications with Boden biogas plant, it is known that part of the biomethane generated is used to power the plant itself. However, as no data was obtained regarding this value, the biogas plant was modelled according to EcoInvent 3.7. The system is modelled using the energy that comes from the Swedish electrical grid and diesel for machines operation needed to process the biowaste. In addition, no allocation of the digestate was used, what might have decreased the impact of the biogas alternative in case it is utilized as a fertilizer. Thus, the impact of manufacturing this fuel is probably lower.

Furthermore, it should also be remarked that natural gas is imported. Therefore, this alternative is not optimal if there is an interest on diminishing the dependency on energy imports. Within the geopolitical situation living nowadays, energy resilience has become a priority and the use of biogas coming from food waste shows up as an attractive alternative. Being able to transform waste into a valuable product and use it locally brings several benefits for a more sustainable economy.

When analysing the manufacture phase of the SOFC, it must be mentioned that some of the processes used in the SOFC stack model did not correspond exactly with the material composition of the parts. As some materials for the SOFC are still developing and can change significantly depending on the manufacturer, LCA databases have not been updated yet. This is consistent with Mori et al. (2021). For instance, there was not any process for the nickel-based oxide doped with YSZ needed to model the anode. This made it necessary to model the processes of other materials with similar properties. Consequently, there might be some gaps in the impact results.

The interconnect and the anode have the highest impact concerning the stack manufacture for all the impact categories considered. Lee et al. (2015) LCA shows the same results. As the electrolyte is made of stainless steel, using recycled material could be an option to reduce its impact. Concerning the anode synthesis, as it was previously mentioned, the model was based on approximations to the real process. Hence, it is necessary to update the LCA databases to be able to assess the environmental impact of these new materials. This could also help deciding on the best material to use when different options are being developed.

Focusing on the balance of plant, there is not any part that stands out in all the categories. The case mainly impacts climate change, water scarcity and resource use energy carriers. The burner and oxidizer have a similar share of the impact in all categories but acidification. The power system mainly impacts minerals and metal resource use. In addition, the heat exchanger is mainly responsible for the acidification category. Also, it was not considered the energy requirements to manufacture each of these parts as no data was possible to obtain. Hence, some of the impact is being neglected. Most of the BoP impact comes from stainless steel and other alloys manufacture, thus being able to reduce the environmental burden of these materials processes production, for instance using green steel would significantly reduce its impact.

Looking to the whole life cycle analysis, stack and balance of plant parts production mainly affects metals and minerals resource use. Hence, recycling, reusing, and remanufacturing becomes a key strategy to mitigate the impact of these parts and keep the materials in a circular loop. Doing this, not only would the environmental impacts of mining activities be minimised, but also mineral resources depletion would slow down and reliance on other countries to get the raw material would be avoided.

Furthermore, since maintenance and replacements of water and air filter was not included, some of the impact was neglected. This must be kept in mind when results are presented, and this data should be included in future studies.

Regarding the air and fuel supply system sensitivity analysis, results revealed that there is a notorious increase on the balance of plant impact when increasing the amount of material use. If this is compared to the fuels manufacture and operational phase, balance of plant impact becomes relatively more predominant for the acidification, particulate matters and, minerals and metals resource use categories.

Waste treatment usually has a relevant impact on the overall results of LCAs. Since there is not a well-defined end-of-life treatment for FC technologies, assumptions on a possible EoL treatment were done. Assuming that steel parts are possible to recycle while the other components of the fuel cell go to incineration, showed that the incineration process has the highest impact for the end-of-life treatment. Analysing these results, developing a specific waste treatment now that FCs are still a novel technology starting to spread seems necessary. Hence, implementing changes on its design to minimise the waste produced and allow keeping the materials used on a closed loop instead of incinerating them is still possible.

Concerning the way of presenting the results, single score results were avoided in the impact assessment section. However, in the Appendix II Figures 37-39 are included. These figures show the single score results to compare the impacts of the SOFC life cycle for the three alternatives. Here, the life cycle impact of the fuel cell as well as the fuel alternatives considered are weighted to a one-dimensional index using EF weighting factors. It is observed that the categories more affected by the natural gas alternative were resource use energy carriers and climate change. Regarding the biogas, climate change is the main responsible of its impact. Analysing the hydrogen option, resource use energy carriers, acidification and climate change are the predominant impacts. Climate change is the category more investigated and with the highest weighting factor given by the impact assessment method selected, hence it was expected a high impact for this category.

The impacts previously mentioned correspond to manufacturing the fuel and operating the fuel cell. SOFC manufacture and disposal have a smaller overall impact. This goes in line with single score results presented by Lee et al (2015). Natural gas single score impact is $25.8 \mu\text{Pt}/\text{kWh}_{\text{el}}$, biogas corresponds to $12.2 \mu\text{Pt}/\text{kWh}_{\text{el}}$, and $97.9 \mu\text{Pt}/\text{kWh}_{\text{el}}$ go to hydrogen. The reason behind avoiding these figures in the impact result section relies on the value based and subjective nature of the weighting factors. Presenting results using the reference unit for each category is considered a clearer way to compare the different alternatives analysed and make evident that there is not an ideal alternative. Improvements need to be made in all parts of the life cycle.

Main limits associated to this environmental assessment are low availability of foreground data. This mainly concerns maintenance of the SOFC, manufacturing of some of the BoP parts, composition of flue gas emitted to the atmosphere, biogas plant operation and EoL treatment of SOFCs. Rough estimation and assumptions were needed to be made due to lack of usable information. Anyway, this study is transparent with all these data gaps with the aim that future studies are aware of them, and the inventory analysis could be further improved and refined.

7. Conclusion and future research

In the present study, an LCA for the BG-15 SOFC is performed. It includes manufacturing end EoL of the stack and balance of plant as well as operation of the system and fuel synthesis. Since this technology is characterized by fuel flexibility, three different fuel alternatives were considered. Biogas alternative is already running in Luleå demo-site whereas natural gas alternative and the possibility of blending it with hydrogen, is expected to be tested in Italy.

Results showed that fuel production is responsible for most of the impacts. Only mineral and metals resource use is mostly affected by building the SOFC. Comparing the three fuel alternatives, hydrogen has by far the highest environmental impact. The comparison of the three alternatives brings hydrogen produced by electrolysis using energy from the Italian grid as the least environmentally friendly alternative. Even if hydrogen avoids polluting emissions during the SOFC operational phase, using electricity coming from fossil-fuels outshines this benefit.

However, hydrogen becomes an attractive option and can compete with natural gas or biogas when renewable energy is used for its manufacture. For this case, there is not a clear alternative that outstands. Oppositely to the hydrogen alternative, some of the natural gas and biogas impacts come during the operation of the fuel cell and their environmental burden mainly differs for the climate change and energy carriers' categories. Producing biogas from food waste avoids energy carriers resource use, carbon emissions going into the atmosphere are biogenic and it also brings the benefit of producing energy locally as well as recirculating materials within the technosphere.

All in all, use of green hydrogen and biogas show up as interesting alternatives but still need improvements to reduce some of the environmental burdens. One main outcome of this study is that to produce electricity using SOFC as energy converters, the energy used to produce the fuels fed into it is a key element. In other words, the electricity to produce the hydrogen and in a lesser degree to operate the biogas plant, will be critical for the environmental performance of these alternatives.

Manufacturing the SOFC mainly impacts metal and mineral resource use. Hence, efforts must be done to reduce raw materials use. This not only would decrease SOFC environmental burden, but also would provide national security ensuring the access to critical minerals.

In conclusion to this work, a few suggestions for further studies are presented. To get a more complete holistic perspective of the system, specific data collection for the values that were obtained from literature as well as maintenance phase, would be needed. Also, direct measurements of the flue gas composition for each alternative are highly recommended. Including allocation of by-products such as heat, and sludge generated in case they are used would be of interest. Lastly, investigating different energy sources to produce biogas and hydrogen as well as considering natural gas market changes would be relevant to assess.

8. References

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Appendix I

Stoichiometric calculations to model the flue gas composition for the biogas and natural gas alternatives are presented in the following lines.

FC efficiency is used to calculate the unreacted fuel following the stoichiometry shown in Equation 9. Input fuel amounts were previously calculated in *Table 24. Mass balance calculations for the SOFC operating with NG, biogas and hydrogen*



The fuel that reacts goes through the steam reforming reaction to produce the hydrogen required for the electrochemical reaction. Carbon monoxide is a by-product of the reaction, and it subsequently reacts with water, producing carbon dioxide (Equation 10). This is commonly known as the water-gas shift reaction.



Lastly, the unreacted methane is assumed to be fully oxidized, transforming into carbon dioxide and water (Equation 11).



To simplify calculations and because of lack of data, it was assumed that all the reactions have a 100% conversion. Though, this might not be the behaviour in real life scenarios. Possible components that could be found in the flue gas are CO that did not get fully oxidized, NO_x, water vapour and nitrogen.

Table 25. Carbon dioxide emitted in the flue gas

	CO ₂ emissions in the flue gas
Natural gas	0.39 kg/kWh _{el}
Biogas	0.36 kg/kWh _{el}

Appendix II

Single score results for all the environmental impact categories included in EF 3.0 are illustrated below.

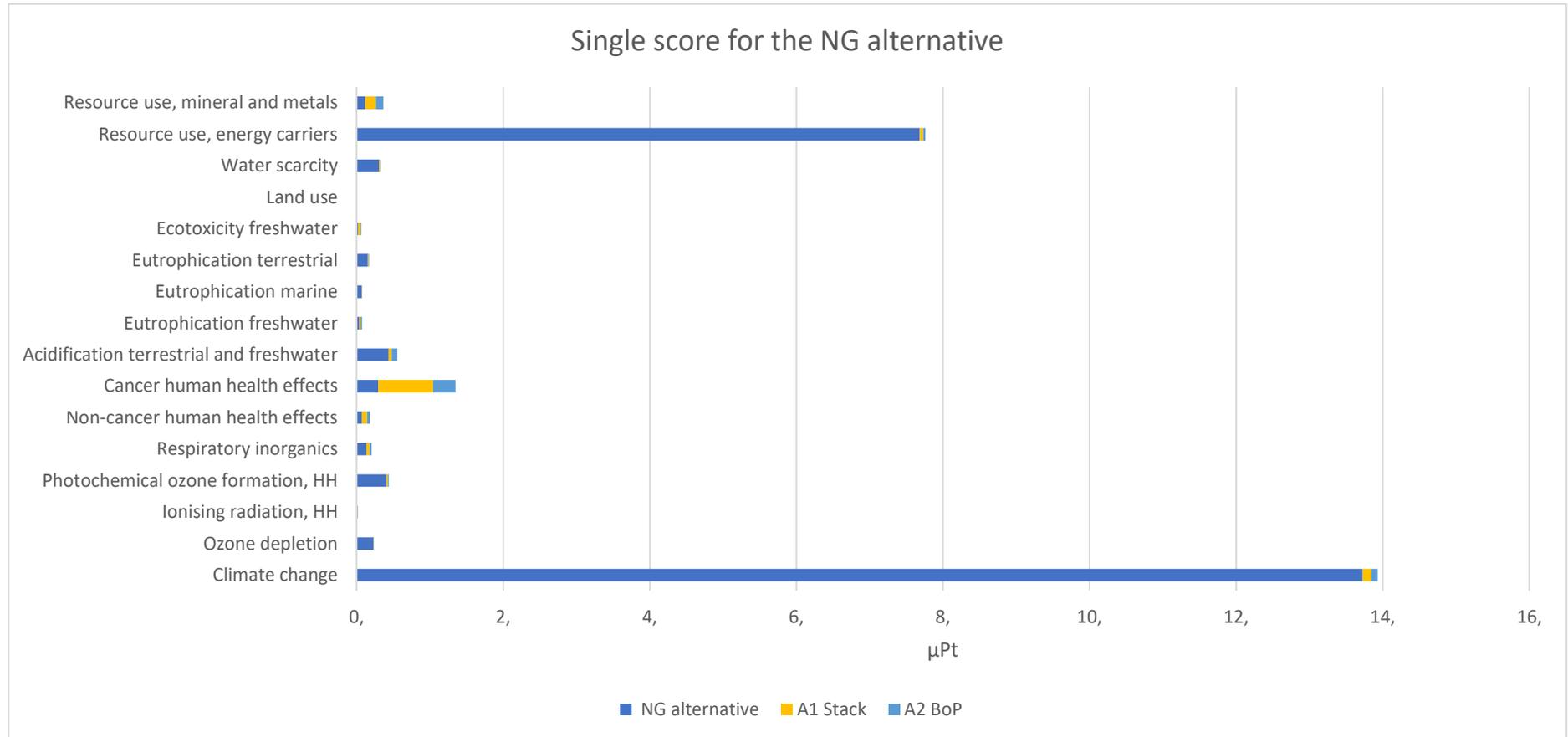


Figure 37. Single score results for the whole life cycle (natural gas alternative)

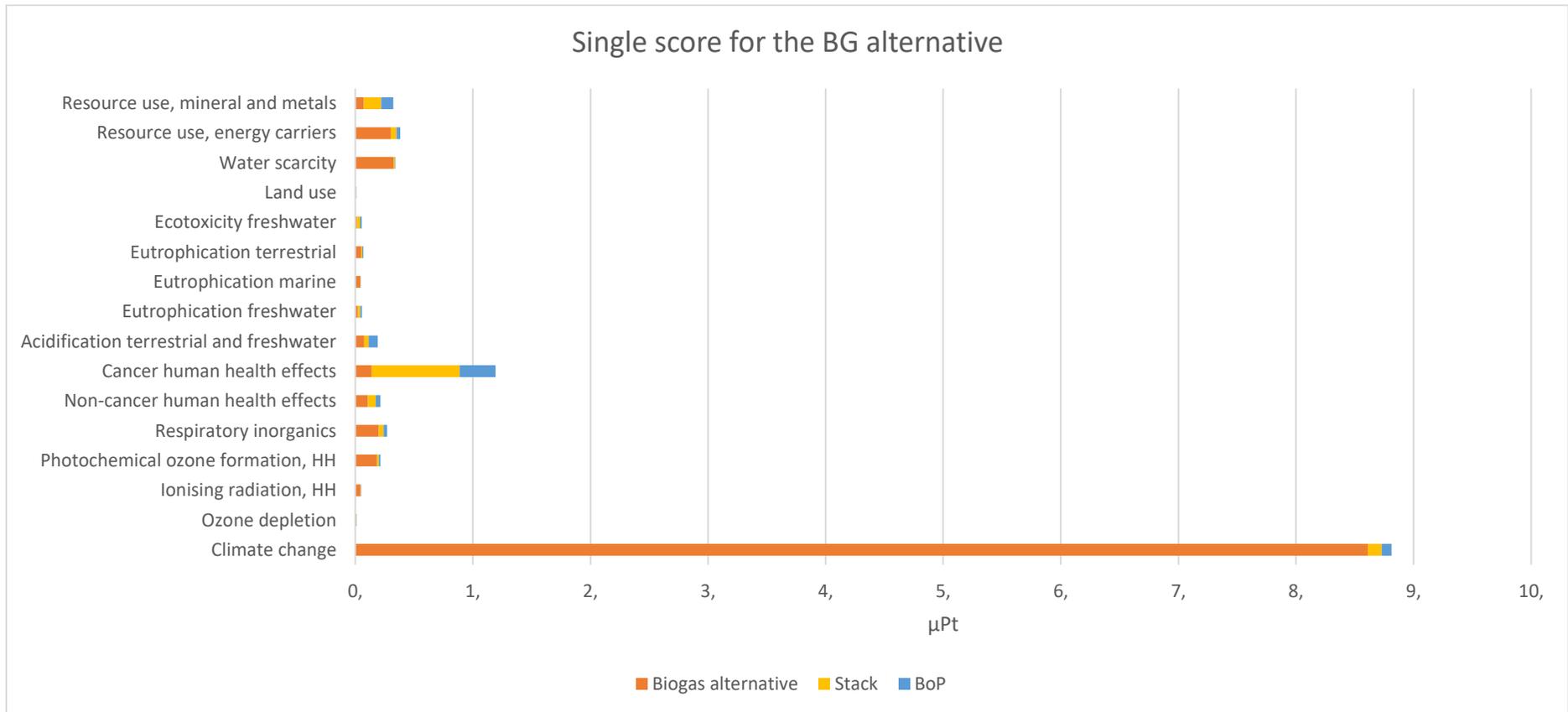


Figure 38. Single score results for the whole life cycle (biogas alternative)

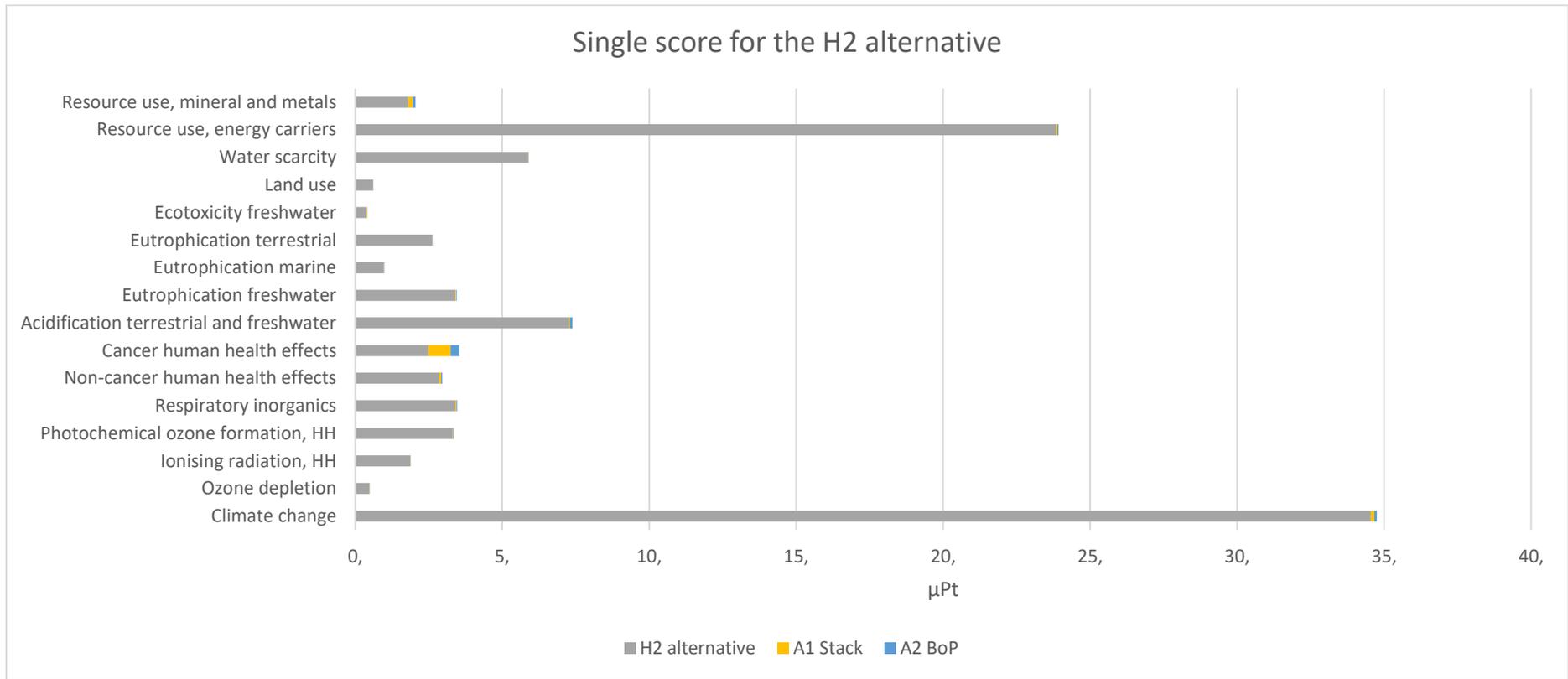


Figure 39. Single score results for the whole life cycle (hydrogen alternative)

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