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Economic Study of a Solid Oxide Fuel Cell Combined Cooling, Heat and Power System

MASTER'S THESIS

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Graz, October 2017

Affidavit

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master‘s thesis dissertation.

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Date Signature

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Abstract

The aim of this thesis is a comprehensive economic study of the Solid Oxide Fuel Cell Combined Cooling, Heat and Power (SOFC CCHP) technology. As a first step the technical background of solid oxide fuel cell and absorption chiller systems is described in order to develop a general understanding of the process, so that the variables, which influence the system design and cost the most, can be identified.

In a subsequent phase all possible applications for the SOFC CCHP system with their operating scenarios will be explored and analyzed. Based on their market potential in Austria, Germany and within the rest of the EU, solutions will be prioritized that offer year-round utilization of the system and highest possible production volumes.

After having determined the best fitting scenarios, the specific system cost for a SOFC CCHP system will be estimated. Once a cost analysis for the fuel cell and the absorption chiller has been done separately the entire CCHP system will be priced with respect to a defined production volume.

In the last phase of the thesis a Total Cost of Ownership (TCO) model will be set up, in order to compare the output in useful energy and the production cost between the SOFC CCHP and a conventional system, e.g. a block heat and power plant with a refrigeration compressor system. The calculation of pay back periods and sensitivity analyses should deliver further development and optimization steps in order to achieve the economic goals.

Kurzfassung

Das Ziel dieser Arbeit ist eine wirtschaftliche Untersuchung eines Kraft-Wärme-Kälte-Kopplung-Systems mit einer Festoxid-Brennstoffzelle (SOFC CCHP). Dazu wird in einem ersten Schritt der technische Hintergrund der Anlage beschrieben, um ein allgemeines Verständnis für diese spezielle Art von Brennstoffzellentechnologie, sowie für die Absorptionskältetechnologie zu entwickeln. Damit können die relevanten Parameter, welche die Systemgestaltung und somit die Kosten am meisten beeinflussen, identifiziert und weiter untersucht werden.

In einem nächsten Schritt werden alle potenziellen Anwendungsmöglichkeiten als auch die relevanten Betriebsszenarien näher untersucht. Basierend auf einer Marktpotentialanalyse für Österreich, Deutschland und der EU wird auf Anlagen fokussiert, welche in großer Stückzahl produziert werden und ganzjährig im Einsatz sind.

Nachdem die geeignetsten Lösungen identifiziert wurden, müssen die spezifischen Systemkosten des SOFC CCHP Systems abgeschätzt werden. Dafür werden zunächst die Kosten für die Brennstoffzelle und die Absorptionskältemaschine separat analysiert, um diese dann in eine Abschätzung für ein kombiniertes CCHP System, unter Berücksichtigung eines bestimmten Produktionsvolumens, überzuführen.

Im letzten Abschnitt der Masterarbeit, wird ein Total Cost of Ownership (TCO) Model vorgestellt, welches einen umfassenden Vergleich mit bestehenden, konventionellen Kraft-Wärme-Kälte-Kopplungs-Technologien ermöglichen soll. Die resultierende Amortisationskalkulation und Sensitivitätsanalyse sollen zukünftige ptimierungsmöglichkeiten identifizieren und somit helfen, die wirtschaftlichen Ziele zu erreichen.

Table of Contents

1 Introduction

The present master thesis was developed in cooperation with AVL List Company. Therefore in this first chapter a short introduction of the company will be given, followed by some information on the initial situation and the goals and scope of this thesis.

1.1 AVL List Company

"AVL List is the world's largest independent and privately owned company for development, simulation and testing technology of powertrains."[1] The company was founded in 1948 and has its headquarters in Graz, Austria. It currently employs over 8000 people in 45 affiliates worldwide. As it can be seen from the following illustration, the scope of business include topics such as powertrain development - hybrid, combustion engines, transmission, electric drive as well as batteries and software for different vehicles, engine instrumentation and advanced simulation technologies. Latest research topics include also different power generation systems for stationary applications.

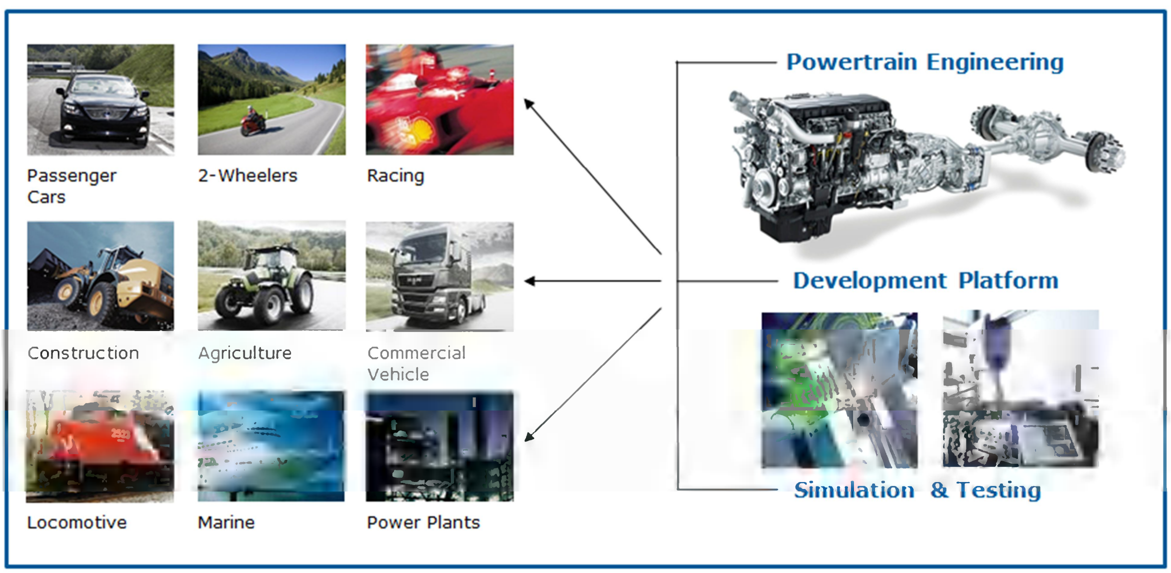

Figure 1-1: AVL Fields of expertise[2]

[1] AVL(2017), https://www.avl.com/web/guest/company, Date of access: 26.1.2017
[2] AVL(2017)

1.2 Initial situation

For the modern industrialized economy to function the electricity is of a foremost importance, therefore interruptions or breakdowns in the supply of electric power will surely lead to an almost complete halt in the public and private life of modern western societies. Though, this applies all the more for countries that are on their way to industrialization and are even more dependent on a continuous power supply as a significant ingredient on their way to economic growth and living standards improvement. As the global economic growth and industrialization are expected to continue throughout the 21th century, it will inevitably lead to rising demand in energy, even if the efficiency of energy conversion and the potential of energy conservation are fully exploited.[3]

It is undoubtedly that the energy industry and particularly the oil and coal industry played a fundamental role, firing the engine of industrialization.[4] In the past two centuries, fossil fuels have been the primary source for power generation, a fact that will hardly change in the foreseeable future. Bearing in mind the environmental implications – the energy production using fossil fuels is the single largest source of emissions, the transition of the global energy system into a sustainable state is becoming a pressing concern and a global policy objective.[5] For this reason it is of highest importance to consider expanding the contribution of other alternatives in the power generation mix.[6]

Through the constant research of energy efficiency and clean energy sources, some potential solutions have emerged, including preservation of energy through higher efficiency, reduced consumption of fossil fuels and growth in the supply of energy by environmental-friendly sources. One of the possibilities worth considering is the fuel cell technology. Fuel cells present one of the cleanest sources of electricity and heat nowadays. Their electrical efficiency can reach over 60% net AC, while producing insignificant amount of air pollutants such as nitrogen and sulfur oxides and relatively small amount of CO_2 Fuel cell systems are well suited for a large range of stationary applications, including industrial power generation, combined heat and power (CHP) plants, decentralized off-grid and back-up energy production, but also in mobile applications (vehicles) and as mobile power generators.[7]

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[3] Cf. Scientific and Technical Committee Euratom (2003), p.(2)
[4] Cf. N.Y. Chen (2000), p. (14)
[5] Cf. L. Baretto, A. Makihira, K. Riahi (2003), p. (267)
[6] Cf. Scientific and Technical Committee Euratom (2003), p.(2)
[7] Cf. A. Hawkes, D. Brett (2013), p.(1)

The main topic of this master thesis is the highly efficient, stationary Solid Oxide Fuel Cell Cooling Heat and Power (SOFC CCHP) system developed by the AVL List Company. This system, running on methane and capable of generating cooling-, heat- and electrical power, is a further development of the existing stationary Solid Oxide Fuel Cell Combined Heat and Power (SOFC CHP) system, with a promising overall efficiency of above 90% in CCHP configuration[8]. To ensure the systems flexibility, the system was adapted to run on different types of renewable fuels like biogas and HVO diesel. The System consists of a high temperature Solid Oxide Fuel Cell and an absorption chiller with a 5 kW cooling capacity, which transforms the excess process heat into cooling power, which can be utilized for different purposes. Depending on the climate conditions the absorption chiller can provide cooling power alone, or both cooling and heating power. In the second application, the system works as a trigeneration unit (electric power, heat and cooling power). Depending on the current application and operation scenario, the system is capable of delivering a constant amount of cooling and heating power and variable amount of electricity. Using the SOFC CCHP unit throughout the whole year allows reaching even higher grade of efficiency and fuel utilization.[9]

1.3 Thesis objectives

The first goal of this thesis is to identify all possible applications and operating scenarios and find out which of those best fit the present SOFC CCHP Technology and allow the highest production volume. The study should consider different power ranges and cooling applications, which will allow exploiting the full potential of this technology.

The second goal consists of a detailed market analysis, followed by an assessment of the market potential of the stationary application of the SOFC CCHP Technology in Austria and in the EU.

A further goal of this thesis is a cost assessment of the two system components separately and then of the system as a whole, based on a production volume estimate.

The last goal of this thesis comprises the actual economic study. It considers an amortization calculation, followed by a sensitivity analysis based on fuel and electricity prices and an overall total cost of ownership of the system. Based on the economic

[8] Information provided in an AVL Interview with Dr. Haut (2017)
[9] Cf. AVL internal specialist

study, future development steps should be identified, which will allow to further reduce the cost of the technology and make it more appealing to future investors.

1.4 Reference Framework

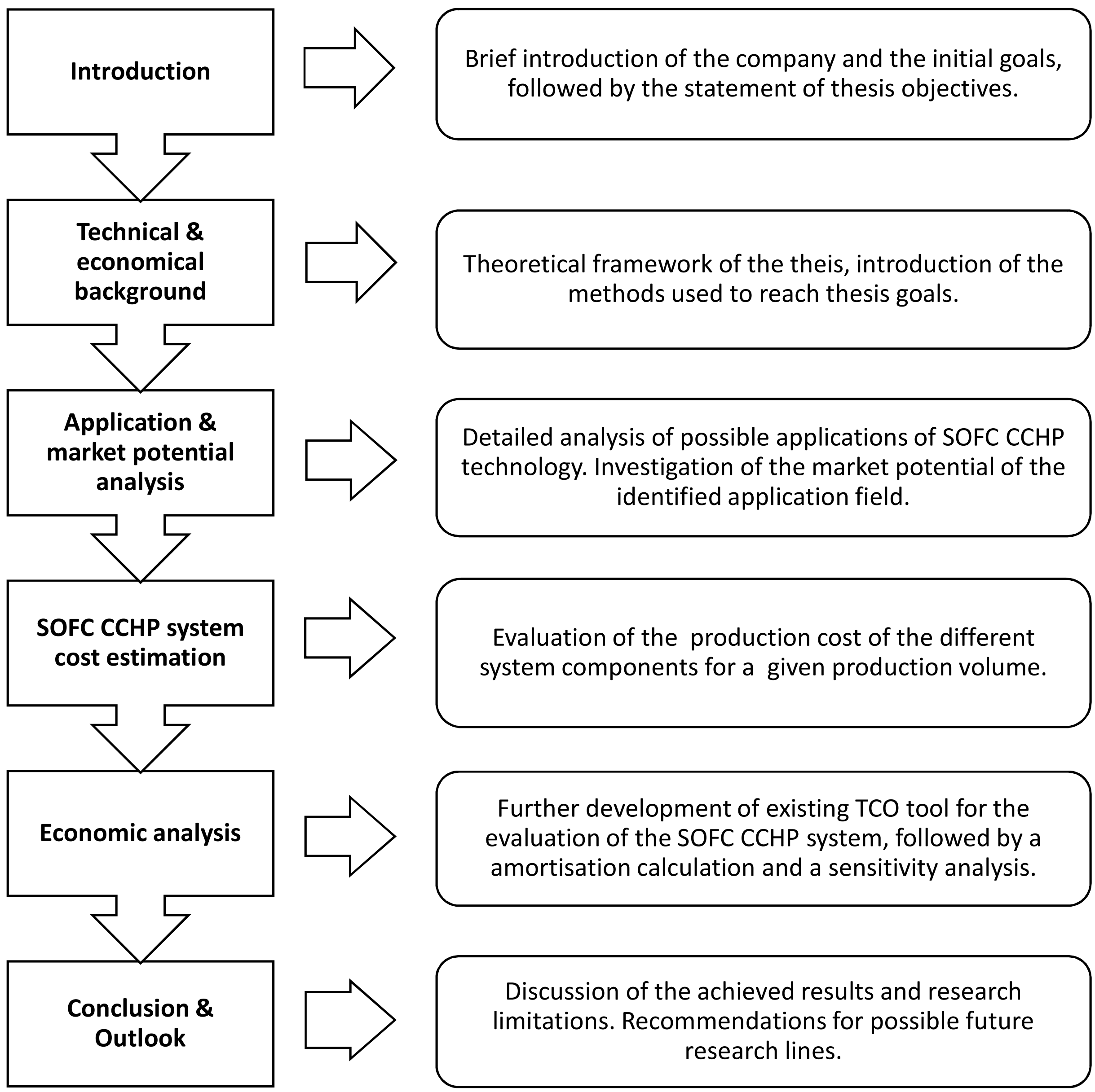

Figure 1-2: Reference Framework[10]

[10] Own illustration

2 Technical and economic background

In this chapter the essential technical foundations of the solid oxide fuel cell combined cooling heat and power (SOFC CCHP) system will be introduced, thus allowing a better grasp of the concept as well as to enable a comparison to the present cooling systems available on the market. This section covers also the economic basics relevant to the approach used to evaluate the commercial and financial viability of the system.

2.1 SOFC CCHP unit

As already mentioned in section 1.2), the AVL List company has developed a highly efficient SOFC CCHP system capable to run on a range of renewable energy sources. The system consists of a solid oxide fuel cell combined heat and power unit (SOFC CHP), which produces electricity and heat as a byproduct and an absorption chiller that makes use of the fuel cell high temperature exhaust gases to produce cooling power. The prototype system is capable of delivering 6 kW of electric power and uses additionally heated air in order to be able to power the absorption chiller. This configuration simulates the exhaust gas mass flow of a bigger 28 kW fuel cell system and together with the absorption chiller delivers 5 kW of cooling power. In this configuration, the system has an electric to cooling power ratio of roughly 5 to 1. Further all technologies relevant to this system will be approached in detail and all key variables that influence the system design and cost will be identified.

2.1.1 What is a Fuel Cell?

The first fuel cell was invented in 1838 by Sir William Grove (1811-1896) and it is a device that converts the chemical energy from a fuel directly into electrical energy, promising low environmental impact and high conversion efficiency.[11] The fuel cell produces electricity by an electrochemical reaction between a hydrogen rich fuel and oxygen, which combine to form water.[12] It can also be seen as a galvanic element, where the reactants are constantly being fed to the electrodes. Because this system avoids the intermediate step of producing heat and mechanical work typical for

[11] Cf. EG&G Technical Services Inc. (2004), p. (20)
[12] Cf. Fuel Cell Today (2011), p. (7)

conventional thermo-mechanical methods, its efficiency is not limited by thermodynamic limitations such as the Carnot efficiency.[13]

A comparison of the conversion process with a typical internal combustion process can be seen in the Figure 2-1 below. This classical thermo-mechanical process also converts chemical into electrical energy, however for this to happen, the fuel must first be burned, releasing polluting agents. Then the thermal energy has to be turned into mechanical and by doing so even the most efficient combustion engines reach efficiency levels of mere 40%. In modern fuel cells on the other hand the electrical efficiency level lays around 60% and when used in CHP configuration levels above 90% are possible.[14]

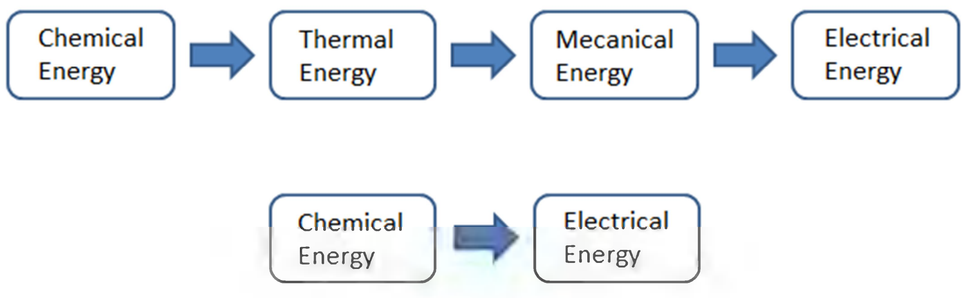

Figure 2-1: Energy conversion in a combustion process (above) and in a Fuel Cell (below)[15]

Electricity from the fuel cell can be used exactly in the same way as power from the grid. Moreover the fuel cell technology has the development potential for commercial size energy production and could therefore serve as reliable base load power source, something that is not possible with the intermittent wind and solar photovoltaic sources.[16] Fuel cells also qualify as distributed energy generation systems and as they usually are constructed next to the load, they do not require transmission line construction, nor do they trigger any transmission losses.[17]

As it can be seen from the following Figure 2-2, each fuel cell consists of two electrodes (positively and negatively charged) and an intermediate electrolyte layer in between that can be of solid or liquid state and the external electric circuit. The chemical reactions between the reactants occur at the electrodes.[18]

[13] Cf. A. Stambouli; E. Traversa, (2002), p. 436
[14] Cf. C. Jackson (2016), p. (27)
[15] Own illustration
[16] Cf. A. Stambouli; E. Traversa, (2002), p. 433
[17] Cf. R. Scataglini et al. (2015), p.(8)
[18] Cf. B. Sörensen (2005), p. (118)

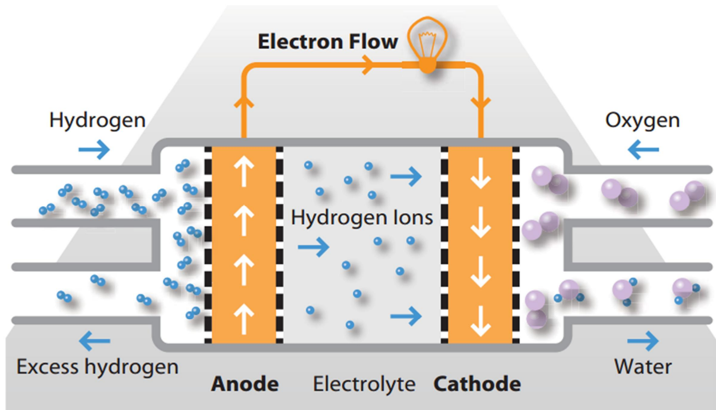

Figure 2-2: Basic Fuel Cell Layout[19]

Oxygen Reduction at the cathode:[20]

$$^{1}/_{2}\ O_2\,(g) + 2H^{+}\,(g) + 2\,e^{-} \rightarrow\ H_2O\,(l) \tag{1}$$

Hydrogen Oxidation at the anode:[19]

$$H_2\,(g) \rightarrow\ 2H^{+}(g)\ + 2\,e^{-} \tag{2}$$

Entire Reaction (Redox reaction), with an electric power flow of $2\ e^{-}$:[19]

$$H_2\,(g) + {^{1}/_{2}}\ O_2\,(g) \rightarrow\ H_2O\,(l) \tag{3}$$

The electrons, which cannot travel through the electrolyte, flow from the anode through an outer electric circuit to the cathode, where they are being used for the redox reaction.[21] The achievable voltage from a single fuel cell lays around 1 Volt. That means that in order to produce useful voltage, multiple cells must be connected in series. In technical solutions, when many fuel cells are connected in series, they form a so called “stack”.[22]

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[19] Fuel Cell Today (2011), p. (8)
[20] EG&G Technical Services Inc.(2014), p.(57)
[21] Cf. AVL Internal Specialist
[22] Cf. J. Larminie, A. Dicks (2003), p. (27)

Fuel cell types

There are several main types of fuel cells primarily classified by the type of electrolyte that is being used, but they are all based around the same design.[23] This classification further determines the type of electro-chemical reactions that run in the cell, the fuel that is being used, the temperature range and required kind of catalyst.[24] In the following section the main characteristics of the different fuel cell types will be described in short.

Proton Exchange Membrane fuel cells (PEMFCs) make use of water-based, acidic polymer membrane as an electrolyte.[25] The next Figure 2-3 shows an illustration of a representative PEMFC.

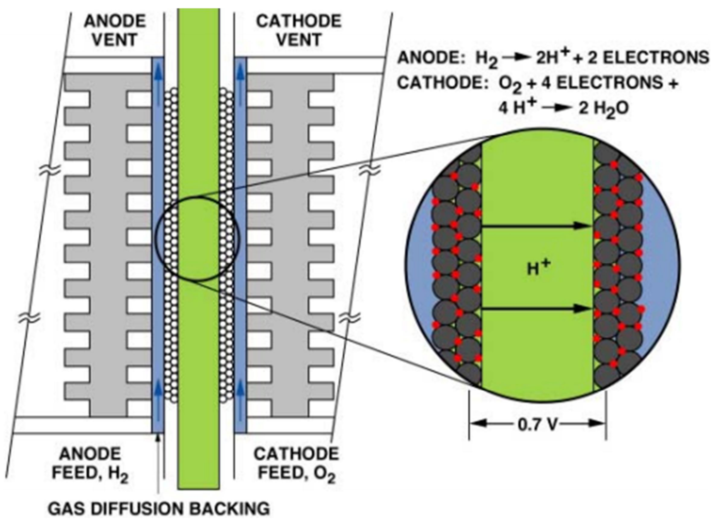

Figure 2-3: Schematic of a typical PEMFC[26]

Because of their operating temperature of around 80°C, PEMFCs count to the low temperature fuel cells, which determine the use of platinum-based catalysts.[27] On the other hand the low operating temperature allows them a rapid startup, much faster than with other cells and eliminates the problems connected with sealing, assembly

[23] Cf. Fuel Cell Today (2011), p. (7)
[24] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells – date of access 31.01.2017
[25] Cf. Fuel Cell Today (2011), p. (8)
[26] EG&G, Technical Services Inc. (2004), p.(89)
[27] C. Jackson (2016), p.(26)

and handling. Their fast startup time of about 2-3 minutes and high power densities make them particularly suitable for light-duty transportation applications.[28]

Unlike other fuel cells which require pure hydrogen, **direct methanol fuel cells (DMFCs)** as the name suggests can be operated on methanol. Since methanol is liquid at room temperature, it can be stored much more easily, thus eliminating the hydrogen high pressure storage problem. Furthermore when methanol is used directly as a fuel, the weight of the system could be dramatically reduced. On the other hand, the biggest problem of the DMFCs is the speed of the fuel anode reaction, which is much slower when compared to other fuel cell types and results therefore in a fuel cell with much less power for given size.[29]

Alkaline fuel cells (AFCs) were one of the first modern fuel cell technologies ever developed, starting in the 1960s.[30] Because of their efficiency rate of above 60%, these fuel cells found strong application in the American space program delivering electrical power on-board the space shuttles. **AFCs** use potassium-hydroxide-water solution as the electrolyte and can employ different kind of non-precious metals as a catalyst.[31]

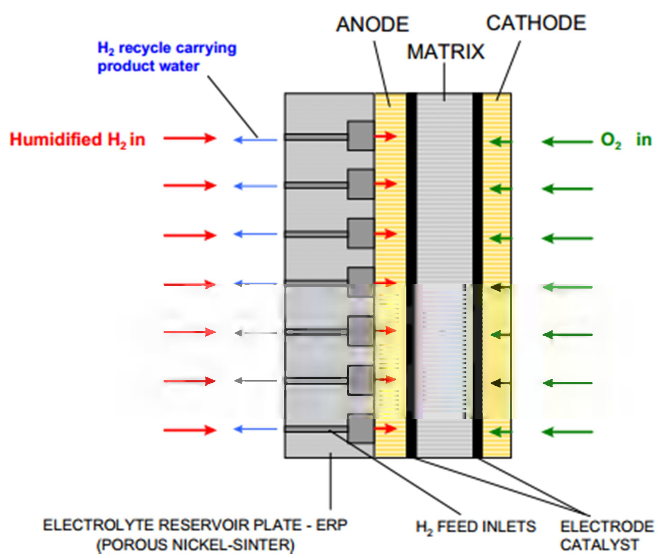

Figure 2-4: Typical AFC configuration[32]

[28] Cf. EG&G Technical Services Inc. (2004), p. (88)
[29] Cf. J. Larminie, A. Dicks (2003), p. (159-160)
[30] Cf. EG&G Technical Services Inc. (2004), p. (113)
[31] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 31.01.2017
[32] EG&G Technical Services Inc. (2004), p. (115)

The biggest challenge that **AFCs** face is their carbon dioxide sensitivity. Even small concentration of CO_2 could in fact dramatically reduce their performance.[33]

The **phosphoric acid fuel cell (PAFCs)** was the first technology to be commercially produced, with over 85 MW of installed capacities.[34] It uses a liquid phosphoric acid as an electrolyte and a porous carbon electrolyte with a platinum catalyst. **PAFCs** can reach 85% overall efficiency when used for co-generation purposes, but they are less efficient at electricity generation, with electric efficiency levels of around 40%. Compared to other fuel cell types **PAFCs** are big and heavy, therefore they are typically used for stationary power generation.[35]

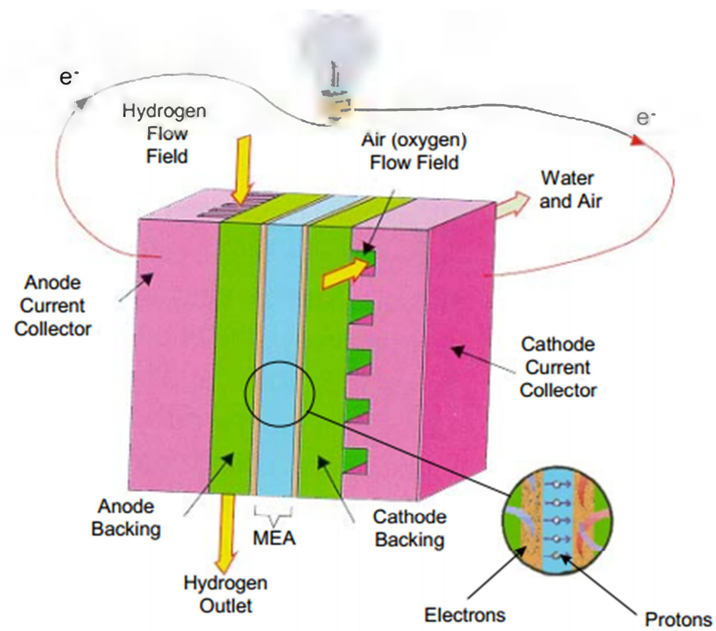

Figure 2-5: PAFCs operation principle[36]

Molten carbonate fuel cells (MCFCs) use an electrolyte consisting of molten carbonate salt mixture such as zirconium dioxide suspended in a porous, ceramic matrix.[37] Their high operating temperature of about 650°C provides them the opportunity to obtain higher system efficiencies and a bigger flexibility in the use of different fuel types – the high temperature enables an internal reforming process of methane into hydrogen.[38] On the downside the high temperature results in even more

[33] EG&G, Technical Services Inc. (2004), p. (123)
[34] Cf. EG&G Technical Services Inc. (2004), p. (130)
[35] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 31.01.2017
[36] Cf. EG&G Technical Services Inc. (2004), p. (131)
[37] Cf. Fuel Cell Today (2011), p. (8)
[38] Cf. EG&G Technical Services Inc. (2004), p. (156)

challenging operation conditions for all components and therefore accelerated corrosion and breakdown of the fuel cell. Currently molten carbonate fuel cells are being developed for coal- and natural gas-based power plants for electrical utility, industrial and military application.[39] The design of the **MCFC** can be seen in the following Figure 2-4.

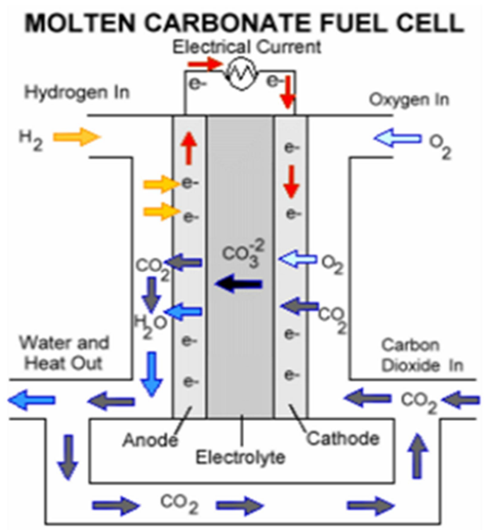

Figure 2-6: Schematic of a MCFC[40]

Solid oxide fuel cells (SOFCs) are one of the most environmental friendly and electrically efficient technologies available nowadays. A **SOFC** uses a solid, non-porous ceramic as an electrolyte and has a very high operating temperature of 650°C - 1000°C.[41] The high temperature of operation excludes the need of precious-metal catalyst and allows for internal fuel reformation, thus reducing the overall system costs. Nevertheless it also results in much longer startup times and places stringent material durability requirements on the system components.[42] The electrical efficiency for this system can reach up to 70% and by recovering the system heat the efficiency rate can even exceed 90%.[43] Large scale fuel cell systems, which generate power from hydrogen, natural gas and other renewable fuels, have already reached pilot-scale demonstration stages in the US, Europe and in Japan. Small-scale systems for

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[39] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 31.01.2017
[40] US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 11.5.2017
[41] Cf. EG&G Technical Services Inc. (2004), p. (197)
[42] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 31.01.2017
[43] Cf. A.B. Stambouli, E. Traversa (2002), p.(439)

the residential sector are being further developed and in countries like Japan with support from the government are already being installed.[44] The following Figure 2-5 illustrates the scheme of a SOFC.

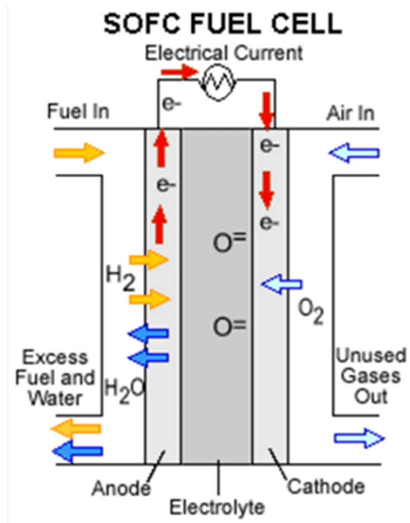

Figure 2-7: Solid Oxide Fuel Cell configuration[45]

The Table 2-1 below summarizes again the main features of the different fuel cell types such as type of electrolyte, electrical efficiency and application.

	MCFC	AFC	PEMFC	PAFC	DMFC	SOFC
Electrolyte	Immobilized liquid molten carbonyte	Pottasium hydroxide	Ion exchange membran	Immobilized liquid phosphoric acid	Polymer membrane	Ceramic
Electrical efficiency	45-60%	45-60%	40-60%	35-40%	40%	50-65%
Operating Temperature	650˚C	60-90˚C	80˚C	200˚C	60-130˚C	1000˚C
Typical electric power	> 200 kW	> 20 kW	250 kW <	> 50 kW	1 kW <	< 200 kW
Applications	Stationary	Submarine, Spacecraft	Vehicles, small stationary	Stationary	Portable	Stationary

Table 2-1: Main characteristics of the different fuel cell types[46]

[44] Cf. US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 31.01.2017
[45] US Department of Energy, https://energy.gov/eere/fuelcells/types-fuel-cells - Date of access:date 11.5.2017
[46] Own Illustration, based on The Fuel Cell Today Industry Review 2011, p.(8)

2.1.2 SOFC CHP system

As a next step in this chapter, a brief explanation will be given on how a SOFC CHP system functions, based on a system developed by the Department of Mechanical Engineering of the Colorado School of Manes in cooperation with Aspen Tech Company. The system depicted in Figure 2-8 operates on biogas and consists of the following main components – a biogas cleanup system, fuel and air compressor units, a fuel pre-reformer, a SOFC stack, an air preheater system, an afterburner and a heat recovery system, as can be seen from the following figure:

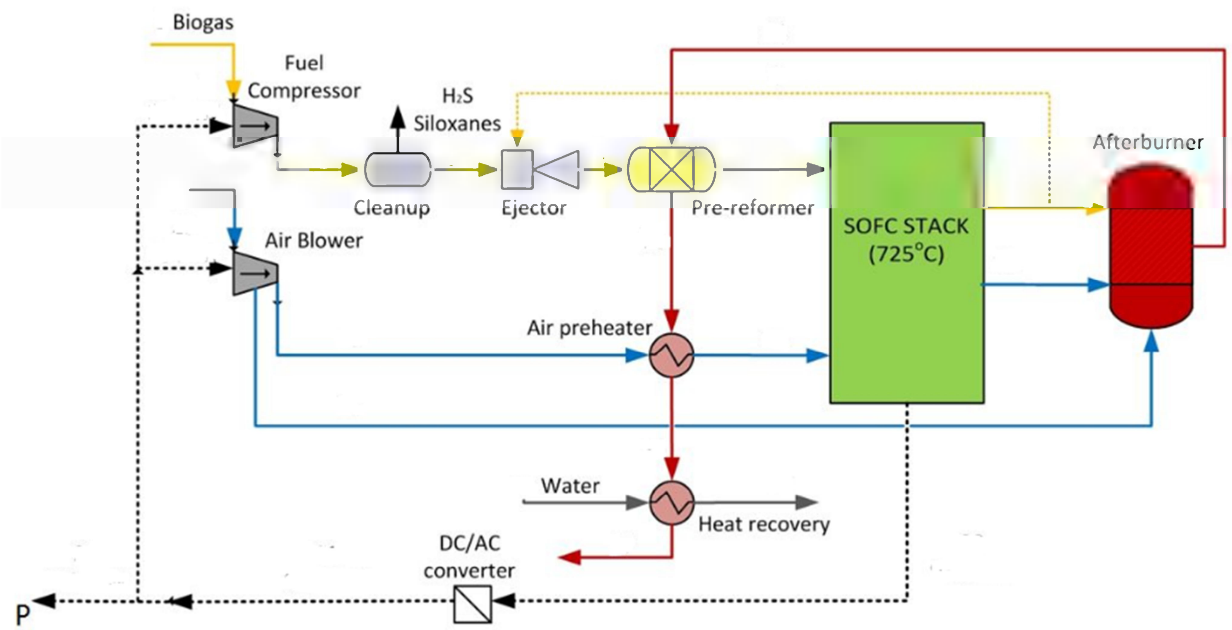

Figure 2-8: SOFC CHP system[47]

In the flowchart, the different flows are depicted in different colors – so the yellow one marks the anode natural gas flow, the blue one refers to the cathode airline, while the red one denotes the exhaust gas flow. In the proposed system, the biogas enters the system at almost atmospheric pressure. The gas is then pre-treated in a cleanup system that extracts the containing impurities that may be harmful to the fuel cell. The purified fuel gas is then mixed with the recycled high-temperature anode gas in the ejector and is then sent to the pre-reformer. In the pre-reformer, some 20% of the methane is transformed to hydrogen, while the rest of it is burned in the afterburner. The hydrogen extracted in the pre-reformer is then fed to the anode of the fuel cell, while the cathode has been provisioned with ambient air, preheated to a temperature

[47] A. Trendewicz, R. Braun (2013), p. (384)

close to the one of the fuel cell operating temperature. The heat available from the afterburner exhaust gases is utilized to heat up the pre-reformed fuel mixture as well as the air, while the rest of the available heat is used for heat recovery. The DC electric power that has been generated in the fuel cell stack is then converted to AC in the power inverter and some part of it is used to power the fuel gas and air compressors.[48]

2.1.3 What is a Chiller?

After discussing the fuel cell component of the system, now the basics of the refrigeration systems will be explained. The term “chiller” refers to the refrigeration machines used in chilled water air- conditioning and refrigeration systems.[49] In these systems, the water is first cooled in the evaporator of the chiller, which is located in a centralized plant. Then the chilled water is pumped to the water cooling coils of the air handling units (AHU) and terminals, where the air is dehumidified and cooled. The water from the coils, which has increased its temperature due to the heat transfer with air, flows back to the chiller, where the process can start over.[50]

Based on their refrigerant cycle, chillers can be primarily classified as heat driven or absorption and electricity driven or vapor compression chillers. In comparison to vapor compression systems that use mechanical power to drive their refrigeration cycle, absorption chillers utilize heat energy available from different sources to generate cooling power and refrigeration effect.[51]

2.1.4 Vapor compression chillers

Generally there are two main types of vapor compression chillers – air- and water-cooled. Air-cooled chillers utilize the air as a cooling medium, which is why they are meant primarily for outdoor installation and operation. These types of chillers reject the heat from the condenser directly into the atmosphere using the natural or mechanically induced air movement. Water cooled chillers on the other hand are generally located within the building intended for cooling and use either a cooling tower, or when

[48] Cf. A. Trendewicz, R. Braun (2013), p. (383f.)
[49] Cf. R. Miller, M. R. Miller (2006), p. (459)
[50] Cf. S. K. Wang, p. (307)
[51] Cf. A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004), p. (685)

available a nearby running water such as a river in order to reject the heat from the condenser.[52]

Chillers could also be classified according to their method of compression. The sort of compressor used depends mainly on characteristics of the application – amount of cooling required, size of the unit, cost and noise requirements. In the refrigeration and air-conditioning industry, there are five basic types of compressors in use today:[53]

- Reciprocating
- Scroll
- Rotary
- Screw
- Centrifugal

Reciprocating units use a piston in a cylinder, working on a two-stroke cycle as shown in Figure 2-9. On the suction stroke as the piston moves down, the suction valve opens admitting vapor refrigerant from the evaporator. When the piston reaches the bottom, the suction valve closes allowing the compression stroke to begin. When the cylinder pressure grows over the one in the discharge pipe, the discharge valve opens and the compressed gas is allowed to the condenser.[54]

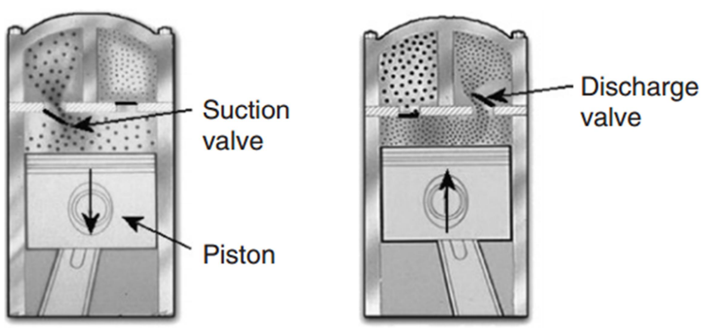

Figure 2-9: Reciprocating compressor[55]

Scroll compressors also called spiral compressors use two scrolls fitted face to face, each of them bound on one side to a flat plate, as shown in the Figure 2-10. The two scrolls are mated together to form gas pockets, which occur between their own lines of contact and the baseplates. The one scroll is stationary and accommodates the discharge port, while the other one is orbiting around the shaft center. During

[52] Cf. B. Mandal, M. Emani (2016), http://www.coolingindia.in/blog/post/id/11394/different-type-of-chillers--their-application, Date of access: 9.10.2017
[53] Cf. A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004), p. (148)
[54] Cf. G. F. Hundry, A. R. Trott, T. C. Welch (2008), p. (43)
[55] G. F. Hundry, A. R. Trott, T. C. Welch (2008), p. (43)

operation time, the refrigerant vapor enters the space between the scrolls through the lateral openings, which are then shut off leaving the gas trapped inside. Due to the successive rotation of the shaft, the volume of the gas gets continuously reduced, until it reaches its maximum pressure. Then the gas pocket opens to the discharge port and the compressed gas is evacuated. [56]

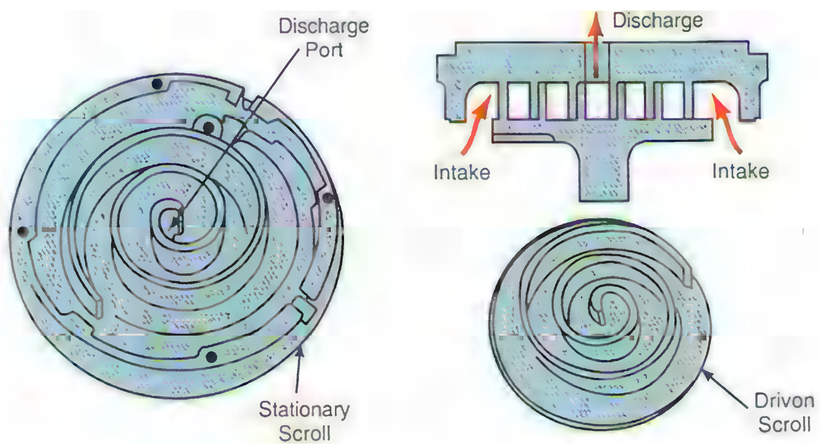

Figure 2-10: Scroll compressor design[57]

The system design of the **rotary compressors** is shown in the following Figure 2-11. As it can be seen from the figure, it uses a rolling piston, which is mounted on an eccentric shaft and a fixed vane, which remains constantly in contact with the piston.

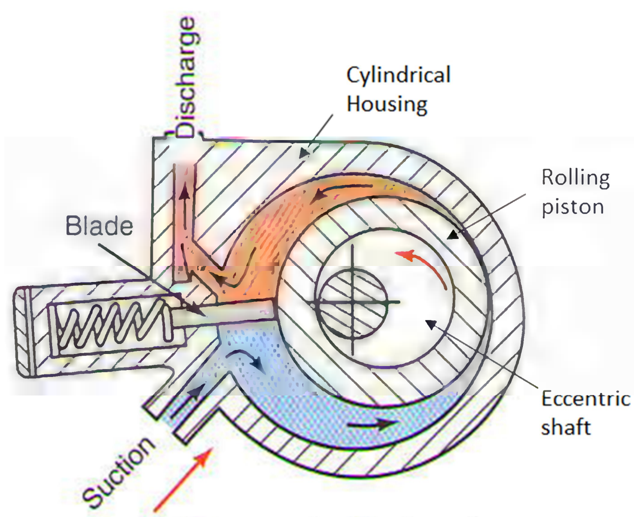

Figure 2-11: Rotary compressor construction[58]

[56] Cf. S. K. Wang (2001), p. (565)
[57] A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (162)

The compression cycle begins with the refrigerant vapor entering the compressor through the suction inlet. Due to the piston's eccentric motion the refrigerant vapor is compressed and when the piston reaches the top of the cylindrical housing, the vapor is forced through the exhaust port.[59]

The **screw compressors** also referred as helical DNA type compressors employ two specially matched helical rotors – a male and a female, which capture the air in a pocket between them as they rotate.[60] The pitch of the helixes is designed in such way, so to enable the arrangement of the inlet and outlet ports at the ends. The solid parts of the screws slide over the inlet and outlet ports, separating the gas pockets and eliminating the need for valves. As the helixes rotate, the volume between the rotors shrinks which causes the gas to compress.[61] From A to E in the below laying Figure 2-12 a complete compression cycle is shown:

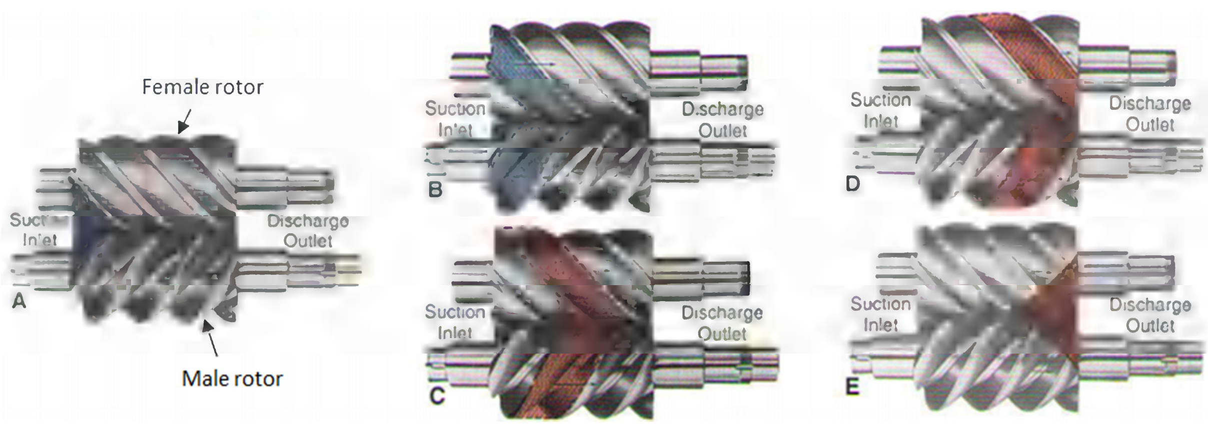

Figure 2-12: Screw compressor [62]

Centrifugal compressors have three basic components – an impeller, a diffuser and a volute, as shown in Figure 2-13. As soon as the impeller starts rotating, the vapor gets accelerated in a circular course because of the centrifugal force. In the diffuser, the accelerated vapor is then slowed down, converting its high velocity into static pressure. In the volute the slow moving high pressure vapor is cumulated and then it is

[58] : A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (160)
[59] Cf. S. K. Wang (2001), p. (564)
[60] Cf. A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004), p. (163)
[61] Cf. G. F. Hundry, A. R. Trott, T. C. Welch (2008), p. (55)
[62] A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (163)

discharged from the compressor outlet. [63] The main advantage of the centrifugal compressor is its simplicity and the only parts that actually wear off are the bearings. [64]

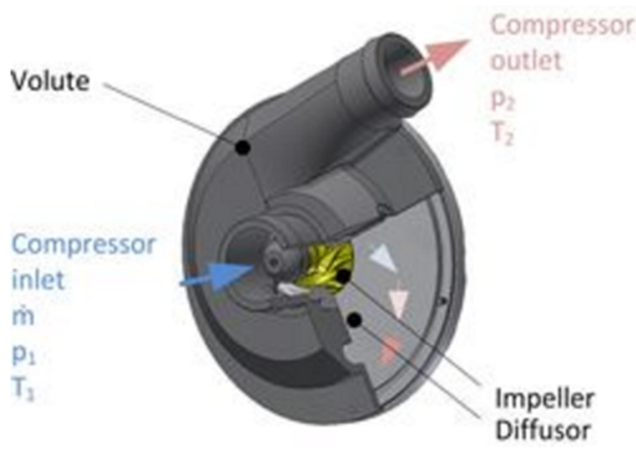

Figure 2-13: Centrifugal compressor design[65]

2.1.4.1 Vapor compression cycle and coefficient of performance (COP)

“Most refrigerants go through a series of processes, absorbing heat from a lower-temperature reservoir and releasing it to a higher-temperature reservoir in such way that the final is equal in all respects to the initial state”.[66]This is the so called closed refrigeration cycle.

In the vapor compression cycle shown in Figure 2-14, the refrigerant goes through four subsequent steps after which it returns to its initial state. The four processes in this cycle include:[67]

- (1) Compression: The refrigerant is compressed to a higher pressure and temperature state.
- (2) Condensation: In the condenser, the latent heat from the refrigerant is rejected to a coolant, thus changing back to liquid form.
- (3) Throttling and expansion: In a metering device, the high-pressure refrigerant is expanded to a lower pressure for evaporation.

[63] Cf. B. Mandal, M. Emani, (2016), http://www.coolingindia.in/blog/post/id/11394/different-type-of-chillers--their-application, Date of access: 9.10.2017
[64] Cf. A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (165)
[65] Celeroton, http://www.celeroton.com/en/technology/turbo-compressor.html - Date of access:06.03.2017
[66] S. K. Wang (2001), p. (419)
[67] Cf. G. F. Hundry, A. R. Trott, T. C. Welch (2008), p. (15)

- (4) Evaporation: The refrigerant evaporates at a lower temperature level than the one of its surroundings, absorbing its latent heat for vaporization.[68]

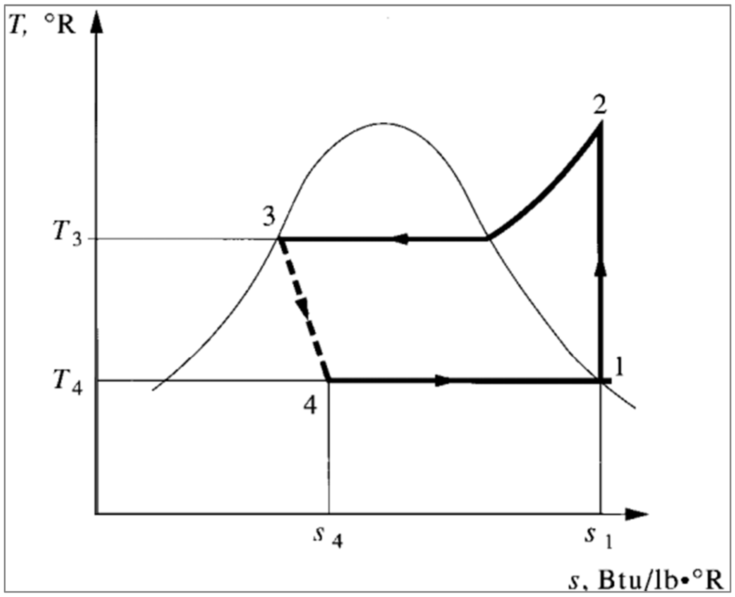

Figure 2-14: Temperature-Entropy diagram for a typical refrigeration cycle[69]

In this process, mechanical energy is introduced as an input and as result heat energy is transferred from the process to the environment. The ratio of these two quantities can be used as an index for the performance of the thermodynamic cycle. Because COP for refrigeration systems can be greater than 1, COP is used as a substitute for the thermal efficiency.[70]

In the literature this is termed as the coefficient of performance (COP). For refrigeration processes it is defined as:[71]

$$\mathrm{COP_{ref}} = \mathrm{Refrigeratin\ effect/Work\ input} \qquad (4)$$

$$\mathrm{COP_{ref}} = \frac{\mathrm{Q_{ref}}}{\mathrm{W_{in}}} = \frac{\Delta \mathrm{Q}_{1,4}}{\mathrm{W}_{1,2}} \qquad (5)$$

[68] Cf. S. K. Wang (2001), p. (419)
[69] S. K. Wang (2001), p. (425)
[70] Cf. S. K. Wang (2001), p. (423)
[71] Ibidem

2.1.5 Absorption chillers

In chemistry, the absorption is a physical (non-reactive) or a chemical (reactive) phenomenon or a process in which atoms, molecules or ions of different substances enter some bulk phase – gas, liquid or solid. Absorption is the condition in which one substance takes in another with their particles having a uniform distribution.[72] In this context, absorption chillers use a mixture of two substances to generate refrigeration effect - a refrigerant (e.g. water, ammonia) and an absorbent (e.g. lithium bromide, water), however the use of water as a refrigerant limits the application to systems with temperatures above its freezing point.[73] The process makes use of the absorbents hygroscopic properties and bases on the absorption and release of water vapor in and out of the solution. Suction and compression of the refrigerant takes place through a "thermal" compressor unit, consisting of an absorber, a solution pump and a generator, as shown in Figure 2-15. As a result two separate cycles are to be distinguished:[74]

- Refrigerant cycle: between the generator, condenser, evaporator and absorber and
- Absorbent cycle: between the generator and the absorber. In order to create a pressure difference between the high- and low-pressure sides, the absorber should be cooled down and the generator should be heated.

Absorption chillers can be classified as direct- or indirect fired. Direct-fired units use as a heat source carbonaceous fuels, which are burned in the unit itself, whereas indirect-fired units use steam or some other fluid that transfer heat.[75] These chillers can further be classified as single- , double- or multi-effect. Single-effect chillers have only one generator and condense the entire vaporized refrigerant in a single condenser. To the single-effect chillers counts also the GAX-circuit. The advantage of this circuit lies in the fact, that the rejected heat from the absorber is used further to heat the generator, thus reducing the external heat demand.[76]

Multi-stage chillers on the other hand, have respectively two or more generator-condenser pairs, where the heat from the higher-pressure condenser serves as energy source for the lower-pressure generator, which reduces the cooling requirement for the vaporized refrigerant.[77]

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[72] Cf. J. McMurry (2003), p.409
[73] Cf. G. F. Hundry, A. R. Trott, T. C. Welch (2008), p. (26)
[74] Cf. N. Krug, C. Hainbach (2008), p. 155
[75] Cf. W. Pohlmann (2008), p. (254)
[76] Cf. New Buildings Institute (1998), p.(4)
[77] Ibidem

Since there is no need of using any chloro-fluorocarbons (CFCs), hydro-chlorofluorocarbons (HCFCs) or hydro-fluorocarbons (HFCs), the cooling process is environment friendly. Moreover renewable source of energy such as biomass and solar thermal as well as different art of industrial waste heat could be utilized.[78]

In order to explain the operating principle of the absorption chiller, a single-effect lithium-bromide/water absorption cycle shown in Figure 2-15 will be used as an example. Its function is based on the thermodynamics of two-substance mixtures. The process follows 4 key steps and as opposed to pure materials, every point of their state is defined by three physical values – temperature, pressure and concentration.

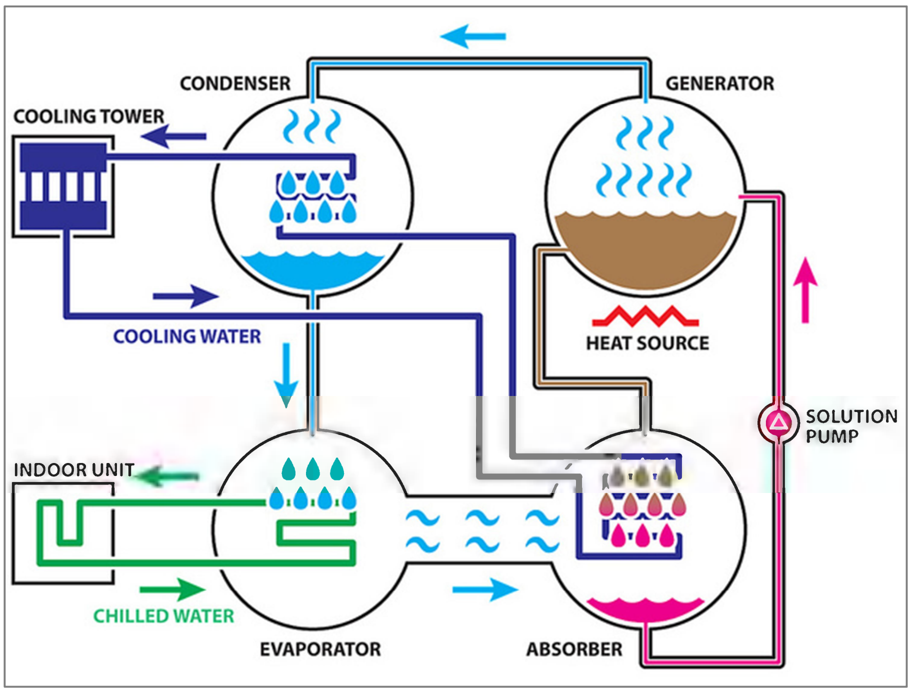

Figure 2-15: Absorption cycle principle[79]

As a first step, the strong lithium-bromide solution (pink) is pumped into the generator (1), where its temperature raises due to the absorbed heat from the generator. When it reaches a certain temperature level, the liquid refrigerant (blue) vaporizes and flows to the condenser and the concentrated lithium-bromide solution (yellow) flows back to the absorber. In the condenser (2) the vaporized refrigerant turns back into liquid, while heat is rejected into to the surroundings. Then the liquid refrigerant is expanded to the evaporator (3) while experiencing drop in pressure and in temperature as well. Here,

[78] Cf. W. Pohlmann (2008), p. (257)

[79] R718, The Basics of R718: the Absorption cycle, http://www.r718.com/articles/3431/the_basics_of_r718_the_absorption_cycle_br, Date of access: 15.6.2017

the liquid refrigerant can absorb the heat energy from its surroundings, while it again changes phase into gaseous condition. The fumes of the vaporized refrigerant then travel to the absorber (4), where they could again be absorbed by the concentrated solution, which would then return to its diluted state. After the absorption, the diluted lithium bromide solution is again pumped to the generator (1), completing the cycle.[80]

Because of the high temperature levels of the SOFC unit's exhaust gases of around 250°C, it seems only logical to use an absorption chiller as an intermediate step to complement the existing solid oxide fuel cell combined heat and power (SOFC CHP) technology. More specifically, the absorption chiller in the SOFC CCHP unit is used to utilize the high grade heat energy coming from the fuel cell exhaust gases, thus producing cooling power. Moreover after powering the absorption chiller, the heat energy of the exhaust gases lies still at a high temperature level of about 100°C, being still usable for heating purposes. In this way the efficiency of the process and the fuel utilization grade could be even further increased.[81]

Although according to studies absorption chillers are available in the cooling capacity range from 13 kW to 12 MW the current market is dominated by larger machines in the range above 300 kW, due to their higher efficiency.[82] In this context, for the SOFC CCHP project a new absorption chiller with a significantly smaller capacity of 5 kW had to be developed. The machine was provided by external contractor working in cooperation with the TU Graz Institute of Thermal Engineering. During the prototype development process, the goal was to create a fully operational SOFC CCHP unit, which would demonstrate the optimal synergy between the two technologies.

2.1.6 SOFC CCHP energy flow and cooling process variables

During the development phase of the absorption chiller, simulations of different operation scenarios with different system parameters and load profiles were conducted. This resulted in different ratios of the produced electric to cooling and heating power as depicted in the following Figure 2-16 and therefore in different SOFC system sizes. As it can be seen from the figure, the fuel cell provides electric power with over 55% electric efficiency and thermal energy in form of the exhaust gases with an average temperature of 260°C. The exhaust gases are further used in the

[80] Cf. R718, The Basics of R718: the Absorption cycle, http://www.r718.com/articles/3431/the_basics_of_r718_the_absorption_cycle_br, Date of access: 15.6.2017
[81] Cf. J. Albert, R. Rieberer (2016), p. (2ff.)
[82] Cf. G. Zdaniuk, A. Crafter, H. Blackwell, CIBSE (2012), http://www.cibse.org/getmedia/5c9a9e15-5103-4b70-8aa1-1b7456fdf9a5/Datasheet-7-Absorption-Cooling – Date of access: 11.2.2017

absorption chiller as thermal input that drives the process. The exact amount of the heat utilized in the absorption chiller can be calculated as the difference of the heat input of the exhaust gases entering and then leaving the absorption chiller at a lower temperature level. On the other hand, as evident from the figure the heat rejected from the cooling process could also be utilized for heating purposes. The issue with this heat source is that it lies at a very low temperature level at about 35°C and might therefore not be suitable for heating purposes in each and every application.[83]

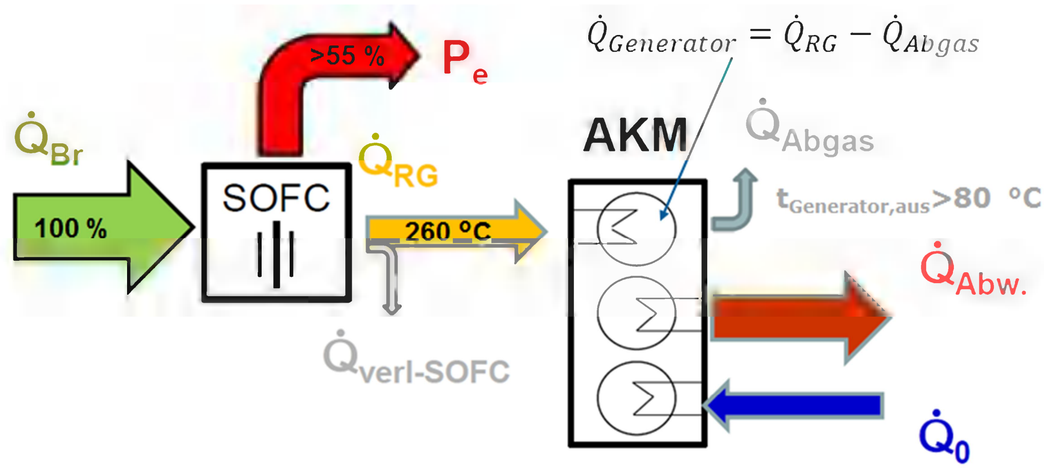

Figure 2-16: Energy flow in the AVL SOFC CCHP system[84]

As a next step the variables, which influence the process performance were considered. Possibly the most significant of them is the temperature level difference Δt between the “cooling” water (t_{cool}) and the “chilled” water ($t_{chilled}$, also called “cold”) that is being determined by the actual application scenario. The cooling water circuit absorbs the rejected heat from both the condenser and absorber of the chiller and cools the system. The chilled water on the other hand represents the useful effect and is used for different cooling purposes. The temperature difference Δt is strongly dependent on the exact application scenario and therefore for the simulation purposes several application scenarios were generated – the first one describes the best case where both cooling and heating power are generated, the second one considers only cooling power at a moderate temperature, while the third one also consider cooling power only but at a very low temperature level. As a result, the best overall efficiency was achieved in the scenario with the lowest difference Δt between t_{cool}/ $t_{chilled}$, when the system was used for both cooling and heating. On the other hand, in the scenario where the system was used for deep refrigeration in a frozen storage, the higher

[83] Information provided in an AVL Interview with Dr. Haut (2017)
[84] G. Zotter (2015), p. (10)

temperature difference Δt led to much lower exhaust gas utilization levels resulting in a drop in the overall efficiency to about 60%. The problem in that case is that the exhaust gases could not be effectively cooled down and most of its thermal energy does not get utilized and in order to achieve the target cooling capacity, the fuel cell must deliver a much higher exhaust gas flow rate and therefore be scaled up proportionally. The next table summarizes the simulation results of the three scenarios in question.[85]

Simulated scenario:	Cooling & Heating	Only Cooling	Only Cooling
Cooling water temperature [˚C]	35 ˚C	29 ˚C	41 ˚C
Chilled water temperature [˚C]	12 ˚C	18 ˚C	-23 ˚C
Temperature difference Δt [˚C]	23 ˚C	11 ˚C	64 ˚C
Cooling power Q_{Eva} [kW]	5	5	4,5
Heating power Q_{Con} + Q_{Abs} [kW]	13,48	-	-
Electrical power P_{el} [kW]	28	19	159,8
η_{el} [%]	60	60	60
η_{total}[%]	99	76	62

Table 2-2: Simulation results of the absorption chiller for constant cooling capacity of 5 kW and different temperature levels of chilled and cooling water[86]

A further variable to consider is the exhaust gas temperature. So far it is known that it would lie around 250°C, but as no real experiments have been conducted so far it is possible for that value to fluctuate. The exhaust gas energy is directly proportional to the gas temperature and its flow rate and a lower gas temperature will result in a higher flow rate demand in order to ensure constant cooling and heating capacity. Simulation at 220°C, 240°C and 260°C show significant shift of more than 10% in the overall efficiency due to the higher exhaust gas flow rate and the resulting higher fuel cell capacity, as shown in the Table 2-3:[87]

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85 Cf. J. Albert, R. Rieberer (2016), p.(11ff.)
86 Own illustration based on J. Albert, R. Rieberer (2016), p. (13ff.)
87 Cf. J. Albert, R. Rieberer (2016), p.(11ff.)

Simulated scenario:			
Exhaust gas temperature [˚C]	220 ˚C	240 ˚C	260 ˚C
Cooling power Q_{Eva} [kW]	5	5	5
Heating power Q_{Con} + Q_{Abs} [kW]	13,47	13,48	13,48
Electric power P_{el} [kW]	38,7	32,5	28
Exhaust gas flow rate m_{fc} [kg/s]	0,07	0,06	0,05
Fuel Energy Q_{diesel} [kW]	64	54	47
η_{el} [%]	60	60	60
η_{total}[%]	88	94	99

Table 2-3: Simulation results of the absorption chiller for constant cooling capacity of 5 kW and different exhaust gas temperatures[88]

In order to measure the process performance three key factors were used. The first is the energy efficiency ratio (EER). The EER describes the efficiency of the refrigeration cycle and is defined as the ratio between the useful energy e.g. the energy absorbed from the chilled water in the evaporator and the energy needed to run the absorption cycle – the energy input from the fuel cell exhaust gases in the generator. For the first scenario, where the absorption chiller is used for cooling purposes only, the EER is calculated as follows:[89]

$$EER_{cool} = \frac{\dot{Q}_{Eva}}{\dot{Q}_{Gen}} \tag{6}$$

And for the integrated SOFC CCHP system, overall system efficiency is defined as the ratio of the generated electrical and cooling power to the fuel energy input:[90]

[88] Own illustration based on J. Albert, R. Rieberer (2016), p. (13ff.)
[89] Cf. J. Albert, R. Rieberer (2016), p.(12f.)
[90] Ibidem

$$\eta_{Sys,cool} = \frac{P_{el} + \dot{Q}_{Eva}}{\dot{Q}_{Fuel}} \tag{7}$$

In a different scenario, when the waste heat energy from the chiller's condenser and absorber is also utilized, an even higher EER and overall system efficiency could be achieved:[91]

$$\eta_{Sys,cool+heat} = \frac{P_{el} + \dot{Q}_{Eva} + \dot{Q}_{Con} + \dot{Q}_{Abs}}{\dot{Q}_{Fuel}} \tag{8}$$

$$EER_{cool+heat} = \frac{\dot{Q}_{Eva} + \dot{Q}_{Con} + \dot{Q}_{Abs}}{\dot{Q}_{Gen}} \tag{9}$$

2.2 Reference trigeneration technology

To enable an accurate evaluation of the SOFC CCHP system economic viability and market potential, it must be compared to a reference system. Therefore the conventional technologies should first be explored and evaluated. However as to this moment no trigeneration systems in serial production exist, the system used as a reference represents a combination of two or more conventional technologies, that when working together achieve a trigeneration effect. Because of the SOFC CCHP system capacity, the reference system is defined as a central air-conditioning system that uses electric power from the gird. Depending on the application and the cooling and heating loads, the air-conditioning system can be either from the DX- or the chilled water type. The differences of the cooling systems will be discussed in the next section. For the northern parts of Europe with prevailing continental climate, the usage of gas for heating purposes and respectively gas heating systems is also very common, therefore in the upcoming economic study, depending on the application scenario gas heating systems could also be included in the trigeneration reference system.

[91] Ibidem

2.2.1 Reference cooling power generation systems

The current European air-conditioning market is ruled by electric driven cooling machines.[92] A possible classification of the available cooling technologies on the market is shown in the following Figure 2-17:

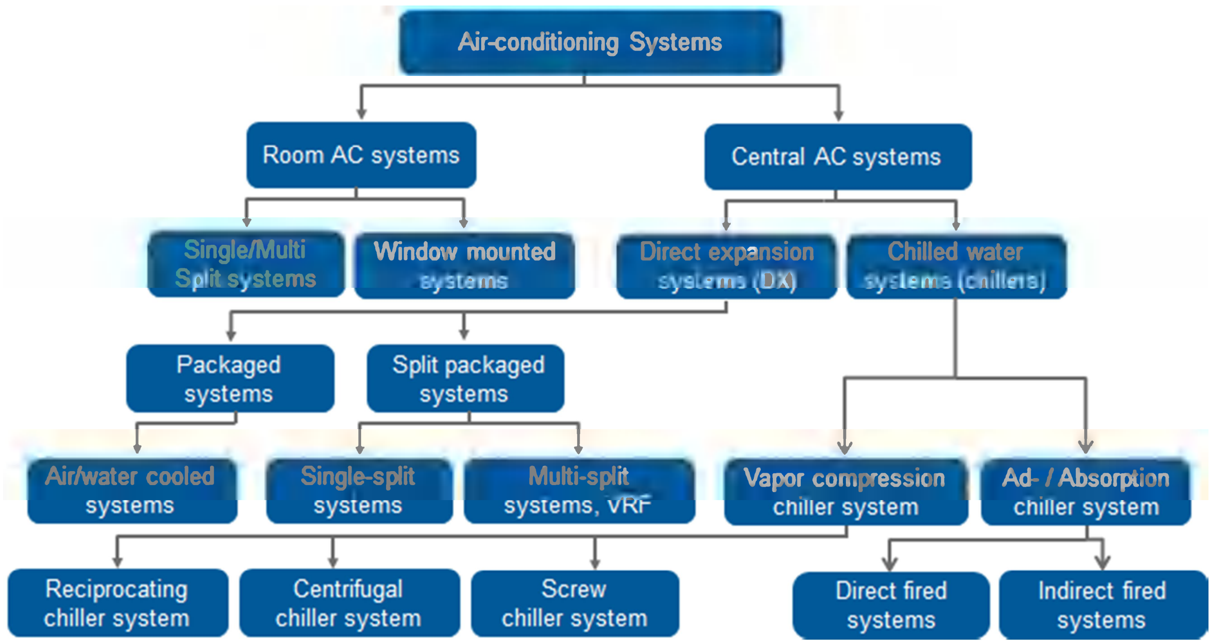

Figure 2-17: Air-Conditioning & Refrigeration technologies classification[93]

As per the above laying figure, the cooling technologies could be classified according to the following main criteria:

- the art of cooling medium used
- the cooling distribution method
- the heat rejection type

2.2.2 Cooling medium

In **direct expansion systems (dx)**, the supply air is cooled by the direct heat interchange with the refrigerant, which flows through the tubes of the finned cooling coil.[94] The term “expansion” relates to the manner used to introduce the coolant into the cooling coil. Just before it enters the cooling coil, the liquid refrigerant is expanded

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[92] European Commission (2016), p.(5)
[93] Own illustration based on J. Adnot et al. (2003), p. (13)
[94] A. Bhatia (2012), p. (2)

through a valve, which reduces the pressure and the temperature of the refrigerant to a point where it is colder than the air passing through the cooling coil.[95] The basic components of a system of this type are: compressor, evaporator, supply air blower fan, filter, condenser and heat rejection propeller fan, as shown in Figure 2-18.

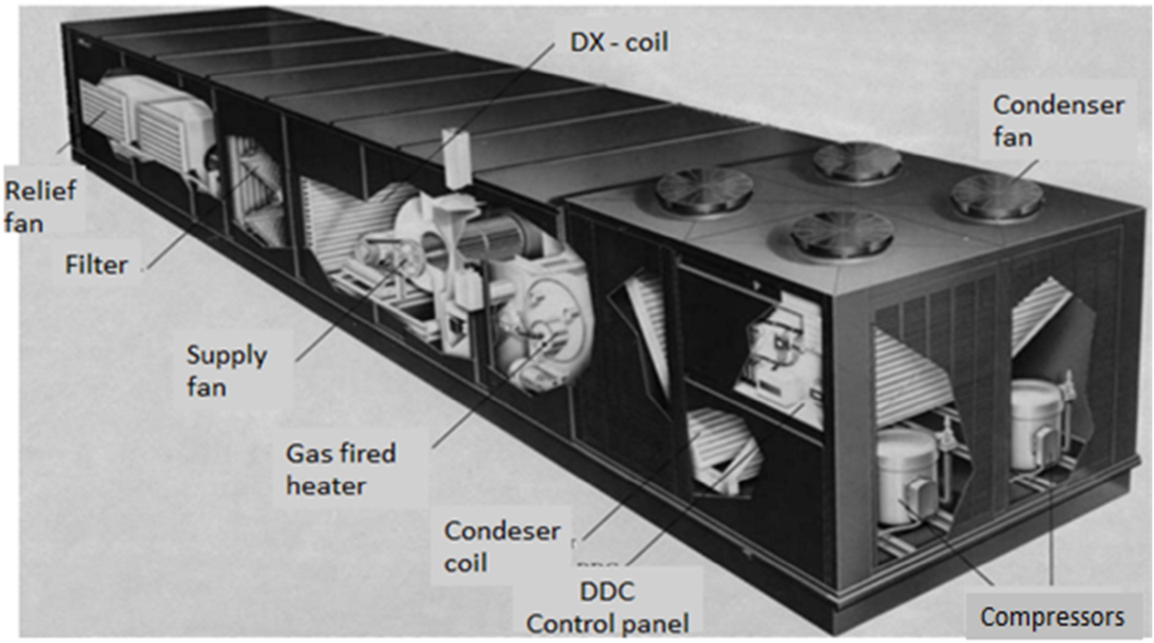

Figure 2-18: Packaged DX unit[96]

The next Figure 2-19 illustrates the concept of the direct expansion air conditioning system. In this scheme, the heat is extracted from the conditioned space and rejected to the surroundings through three loops of heat transfer:[97]

- First the supply air transfers its heat to the refrigerant and the cooled air afterwards is sent back to the room
- In the middle, the compressor drives a closed loop cycle, where the vaporized refrigerant is sent to the condenser and then back to the evaporator in liquid state
- In the last loop, the condenser fan forces the air through the condenser, where the heat of the coolant is rejected to the outdoors. The refrigerant is cooled down and expanded through a valve to the evaporator.

95 Cf. Trane Air Conditioning Clinic (2016), p.(30)
96 S. K. Wang (2001), p. (771)
97 A. Bhatia (2012), p. (2f.)

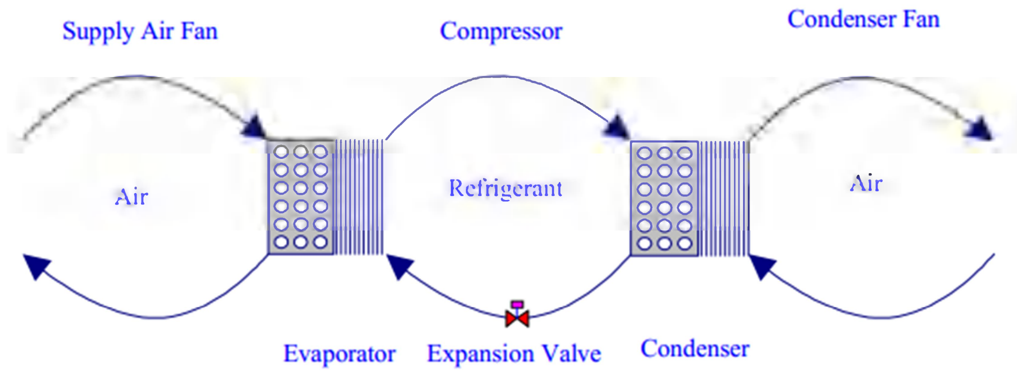

Figure 2-19: Conceptual view of the DX air-conditioning system[98]

Packaged units belong to the most common types of DX systems. “These air conditioners are characterized by being relatively small self-contained units, or split units that together make a complete functional unit, containing all the components necessary to provide space cooling.”[99] These systems are factory assembled and vary in capacity and types. Depending on the applications requirements, these systems are available as **window air conditioners**, air conditioners of the split type e.g. **single splits**, **multi splits**, **VRF**, **heat pumps** and **ductable systems**.

The “heat pump” term refers to DX systems, which could also be operated in reverse cycle. Through the implementation of a special 4-way reversing valve, heat pumps can reverse the heat flow, thus enabling the extraction of heat from the surroundings and rejecting it inside of the space to be this time heated. Heat pumps are able to supply both heating and cooling from the same device and thanks to the compression heat, have a higher heating efficiency.[100]

Room air conditioners e.g. window air conditioners supply cooled air to single rooms, rather than the complete building. They can be switched on only when they are needed and are relatively inexpensive. Their cooling capacity is adjusted by switching on-and-off the compressor and it is also possible to control the fan speed. In the **split** system variation, the system consists of an outdoor condensing unit, often mounted on the rooftop (e.g. **Rooftop units**) and a single (e.g. **Single splits**) or multiple (e.g. **Multi splits**) indoor air handling units that together make a complete functional unit, as shown in Figure 2-20. Packaged systems with two or more air handling units (evaporator), which are powered by a single condensing unit, are referred as **Multi splits.** The liquid refrigerant from the condenser flows through the expansion device

[98] A. Bhatia (2012), p. (2)
[99] G. Hundry, A. Trott, T. Welch (2008), p. (316)
[100] A. Bhatia (2012), p. (14)

and then the mixture of flash gas and cold liquid is supplied to each of the air handling units on the cooling circuit.[101]

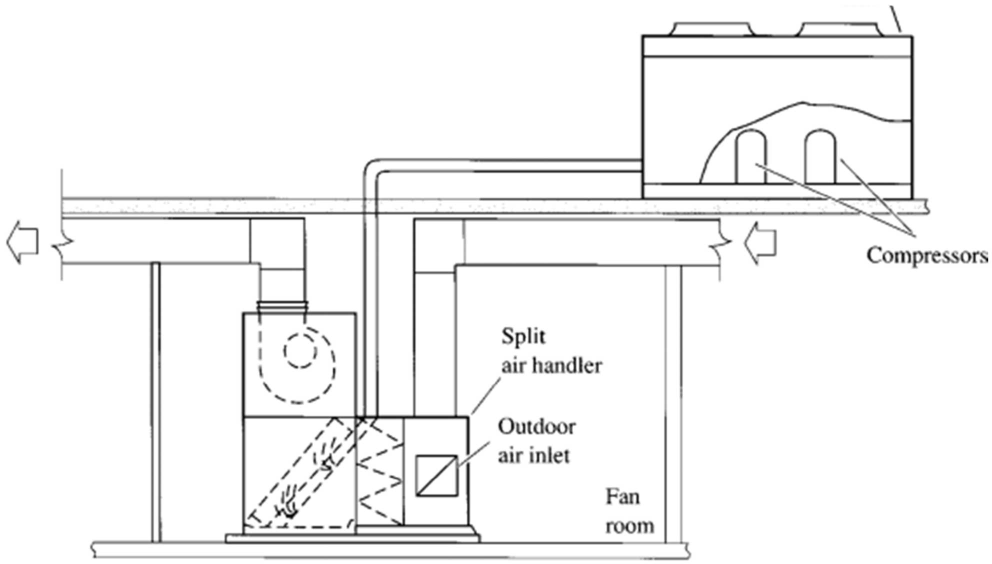

Figure 2-20: Typical single split packaged unit[102]

An interesting development of the multi-split technology is the variable refrigerant flow or **VRF** system. This type of system usually consists of a central refrigerant compressor, which is connected to a series of evaporators serving different spaces. The VRF term relates to the system's ability to adjust the amount of refrigerant flowing to each evaporator, thus enabling the use of evaporators of different capacities and configurations and providing individual zone comfort and coinciding heating and cooling in different zones.[103] Opposed to multi split systems, where each indoor unit is connected individually to the outside unit, in the VRF system each indoor unit is connected to a common refrigerant network as shown in Figure 2-21. This fact provides the VFR system the ability to control the flow of the refrigerant to each evaporator separately through a pulse modulating valve (PWM), which opens and closes according to the information from sensors placed inside each evaporator.[104]

[101] Cf. G. Hundry, A. Trott, T. Welch (2008), p. (316)
[102] S.K. Wang (2001), p. (775)
[103] Cf. A. Bhatia (2014), p.(2), http://www.seedengr.com/Variable%20Refrigerant%20Flow%20Systems.pdf
[104] Cf. A. Bhatia (2014), p.(15

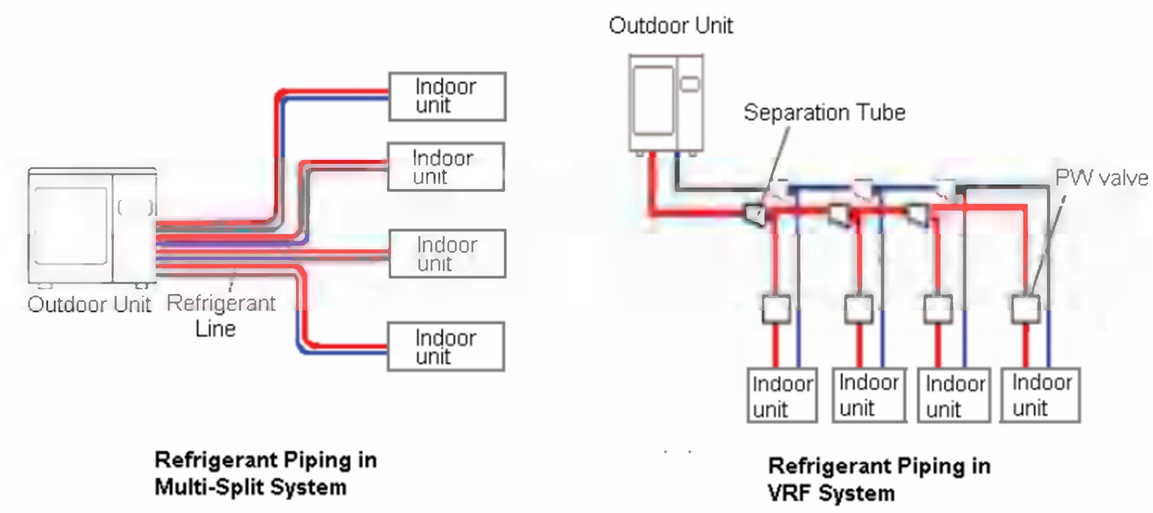

Figure 2-21: Comparison of the refrigerant piping of a VRF to a Multi-Split system[105]

In VRF systems, the outdoor unit is connected to the indoor units through a control wire and receives information about their demand. It can therefore respond by varying its compressor speed in order to match the total cooling demand. Because of the use of variable speed compressors, VRF systems can maintain very precise temperature control. A further improvement over multi-split systems is that the VRF technology minimizes the refrigerant piping and copper tubing through the connection of the indoor units to a common refrigerant network, which maximizes the system efficiency.[106]

The main restricting factor of direct expansion systems is the length of their refrigerant piping. In these systems the refrigerant has to flow through the entire system until it reaches the air handling units, which causes drop in its pressure. In some cases, it is possible for the pressure drop to be so high that the refrigerant does not reach the air handling unit, thus leading the entire cooling system to failure. For this reason the length of the refrigerant piping and the length of the tubing between the condenser and the air handling units should be kept to a minimum, which limiting the application of direct expansion systems.[107] The distance constraint between the condenser and the cooling coils in DX systems is limited to about 35 m. [108]

In **chilled water systems** on the other hand, water is used as the cooling medium. Chilled water flows through the cooling coil, thus cooling the supply air. Since the

[105] A Bhatia (2014), p. (9)
[106] Cf. R. Hitchin, C. Pout, P. Riviere (2012), p(6)
[107] Cf. P. Ananthanarayanan (2013), p.(292)
[108] Cf. A. Bhatia (2012), p.(7)

water needs to be cooled down to a lower temperature, a cooling plant that is typically referred as a chiller is required.[109] The components of the chilled water system usually include chiller, air-handling units with chilled water coils, chilled water piping with chilled water pumps, condenser water piping with a condenser water pump and a cooling tower to reject the heat.[110] All of these components can be seen in the next Figure 2-22, which illustrates the chilled water system concept.

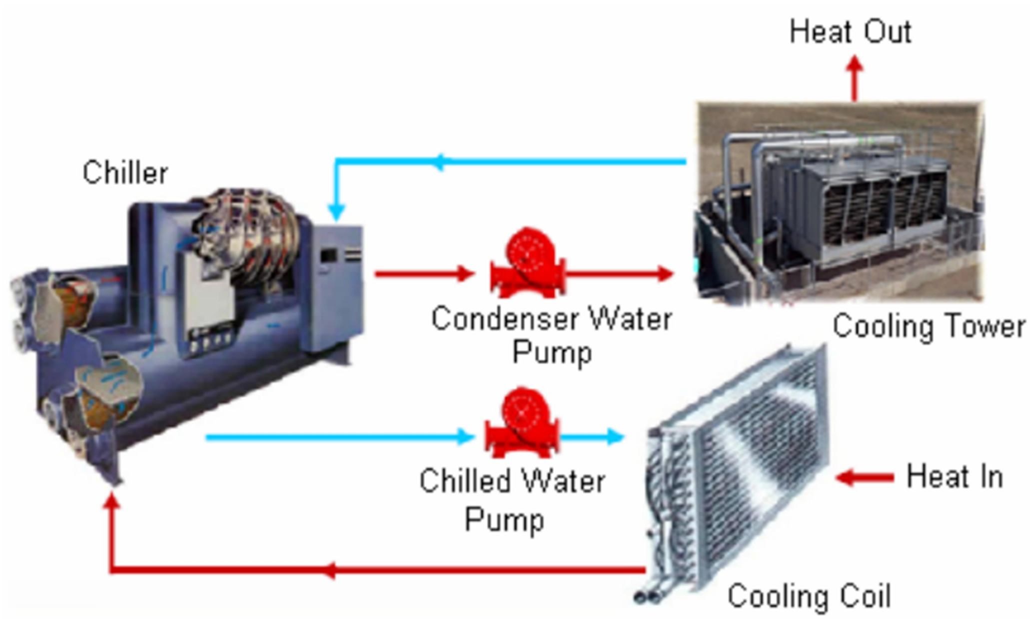

Figure 2-22: Chilled water air conditioning system[111]

In the chilled water system the heat is extracted from the space and rejected to the surroundings following the scheme illustrated in the following Figure 2-23. The chilled water, which is produced in the evaporator of the refrigeration cycle, is pumped to the cooling coils where it cools the supply air. The heat of the returning chilled water is absorbed by the refrigerant and then in the condenser is rejected to the cooling water. The condenser pump pumps the cooling water to the cooling tower where its heat is transferred to the surroundings.[112]

[109] Cf. S.K. Wang (2001), p. (307)
[110] Cf. A. Bhatia (2012), p.(10)
[111] A. Bhatia (2012), p. (10)
[112] Cf. A. Bhatia (2012), p. (11)

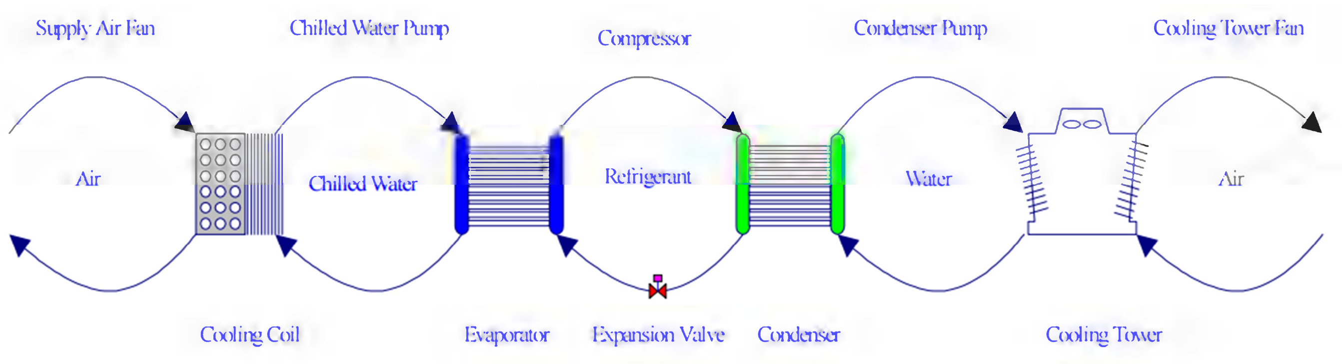

Figure 2-23: Conceptual view of the chilled water air-conditioning system[113]

The key advantage of the chilled water systems towards direct expansion systems lies in the much smaller circuit flow of the refrigerant. As it can be seen from the diagram, the refrigerant in the middle flows in a close loop. These systems usually have all the components of their refrigeration system in a single plant room, thus eliminating the problem with the length of the piping, since it is the chilled water that travels to the cooling coils. The only thing that limits the length of the piping is the capacity of the chilled water pump. For this reason, chilled water systems are most suitable for large multi-story buildings.[114] The figure below illustrates an air-cooled chiller on the left and a water-cooled one on the right:

Figure 2-24: Air-cooled 600 kW chiller (left) and water-cooled 250 kW chiller (right)[115]

[113] A. Bhatia (2012), p. (11)
[114] Cf. P. Ananthanarayanan (2013), p.(290)
[115] G. Hundry, A. Trott, T. Welch (2008), p (173-174)

2.2.3 Cooling distribution method

Generally air conditioning systems can be divided in all-air and air-water systems depending on the cooling distribution method.[116] In all-air systems, all the conditioned air is provided by a central air handling unit and is then circulated round the building. These systems are often adopted for the cooling of large open spaces such as theaters, cinemas, factories and open plan offices.[117]

Typically chilled water is used to feed the cooling coil of the air handling units, although these systems when equipped with a heating coil could also provide hot air heating. The most simple all-air system is the constant volume (CV) system. A CV-system delivers a constant amount of supply air throughout the operating period and varies the supply air temperature to maintain the predetermined space air temperature during part-load operation in order to match the reduction of space load.[118] A more sophisticated cooling process control is provided by the variable air volume (VAV) system. This is an air system, which varies the volume flow rate of the supply air to match the reduction of space load.[119]

In air-water systems chilled water is prepared centrally and then it is distributed to different locations throughout the entire building. Air-water systems however need remote air handling units, also called terminal units. Air-water systems are also capable of providing heating, which can be done by the same terminals or by the use of additional radiators. The most commonly applied terminal units are: fan coils (water to air heat exchanger with a fan to force convection), radiant cooling panels (e.g. cold ceilings), induction units, embedded systems (cold pipes, installed under the flooring) and passive and active chilled beams. Air-water systems are more suitable for buildings with many premises requiring individual control including heating in some zones and cooling in other.[120]

2.2.4 Heat rejection method

Depending on the cooling medium used, condensers can be classified as:

- Water cooled condensers
- Air cooled condensers

[116] Cf. P. Riviere, ARMINES (2012), p. (12)
[117] Cf. G. Hundry, A. Trott, T. Welch (2008), p. (306)
[118] Cf. S.K. Wang, p.(994)
[119] Cf. S.K. Wang, p.(1035)
[120] Cf. A. Bhatia (2012), p. (8)

- Evaporative condensers

In water-cooled systems, cooling water is used to remove the condensing heat from the coolant of the refrigeration system. There are two types of water cooled condensers, which are widely applied for air conditioning and refrigeration – the shell-and-tube and the double-tube condenser.[121] The double tube condenser is shown in Figure 2-25.

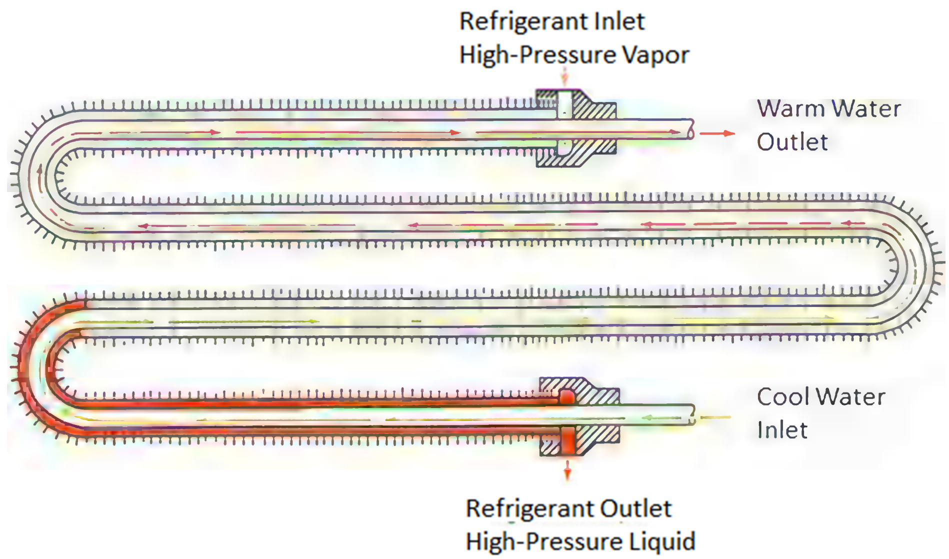

Figure 2-25: Double-tube condenser flow diagram[122]

The condenser of this type consists of two tubes, one inside the other. The cooling water flows in the inner one, while the refrigerant flows in the space between the two tubes in a counterflow arrangement.[123] The cooling water can be provided by natural sources such as lakes, rivers or wells near the refrigeration plant or also from a cooling tower. The use of a river, lake, sea or ground water is referred as a once-through method, as the water cannot be recirculated and used again as cooling source.[124]

Air-cooled systems on the other hand use air to extract the latent heat from the refrigerant vapor during condensation. The system generally consists of condenser coil connected in series with a sub cooling coil, which are typically equipped with copper tubes and aluminum fins. Air-cooled systems can be divided in finned-static - cooled by natural air flow and finned-forced that use propeller fans to force cooling air

[121] Cf. S.K. Wang, p.(484)
[122] A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (140)
[123] Cf. S.K. Wang, p.(484)
[124] Ibidem

through the coil[125]. As shown in Figure 2-26, in order to provide an even airstream through the coil, the fan is usually located downstream from the coil.[126]

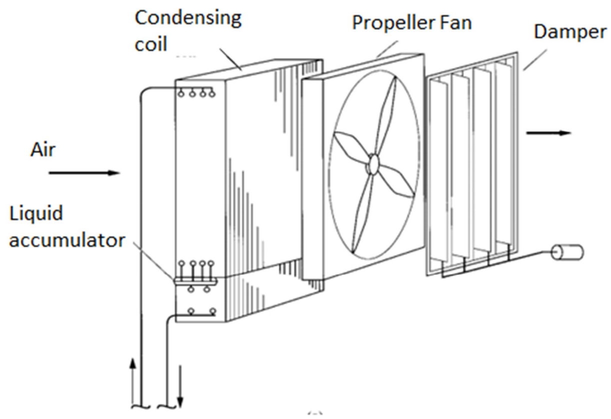

Figure 2-26: Finned-forced convection condenser[127]

An evaporative condenser is a combination of a condenser and a cooling tower.[128] Figure 2-27 illustrates the cooling effect of the water, which is applied by the nozzles directly on the outside surface of the cooling coil. Due to the evaporation of the water, the heat is extracted through the wet condensing coil surface. The excess water, which is not evaporated, is collected in the water basin below the coils and then is pumped back to the nozzles.[129]

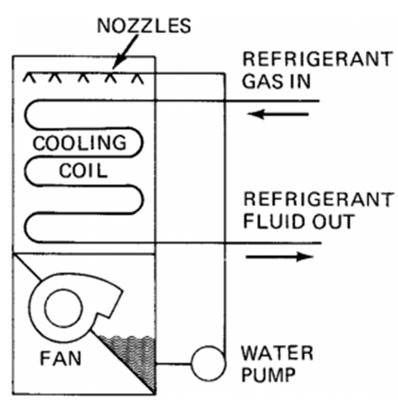

Figure 2-27: Evaporative condenser[130]

[125] Cf. A. D. Althouse, C. H. Turnquist, A. F. Bracciano (2004) p. (139)
[126] Cf. S.K. Wang, p. (488)
[127] S.K. Wang, p. (489)
[128] Cf. R. Miller, M. R. Miller (2006), p. (252)
[129] Cf. S.K. Wang, p. (492)
[130] R. Miller, M. R. Miller (2006), p. (252)

2.3 Economic study

In this chapter, the economic basics, following the structure of the corresponding practical part of the thesis are elaborated:

- Application analysis and market potential
- Cost estimation of the SOFC CCHP system
- TCO model of the SOFC CCHP system

The first part consists of a broad market study, with the goal to identify the possible applications for this technology and their market potential within the EU. In a subsequent phase, the specific system costs of the system components should be estimated under consideration of a certain production volume. The last section covers the topic of the total cost of ownership of the system and provides a comparison of the SOFC CCHP overall costs with a conventional technology costs over a specific time period.

2.3.1 Market research

The market research is an activity which belongs to the marketing, and marketing itself is a philosophy on how to succeed in business. As a philosophy, marketing points out the importance of using markets and customers as to guide business decisions.[131]

From this point of view, the aim of the market research is to gain information on specific markets and enquiry groups, in order to enable a decision based company management. Therefore in the company practice, market researchers should be able to give a prompt and goal orientated feedback on specific issues and also be able to timely recognize future market development and trends.[132]

2.3.1.1 Tasks and Functions

Before the market research tasks could be defined, the general conditions of how management decisions nowadays are taken should be brought to mind. Because of the growing volatility of the markets and the ever shorter product lifecycles, two problems for the decision making emerge – the problem of the uncertainty and the

[131] Cf. E. McQuarrie (2005), p.(3)
[132] Cf. R.Olbrich, D. Battenfeld, C. Buhr (2011), p. (3)

problem of the incompleteness.[133] Both of these problems base on the incomplete information stand and lead to a subjective feel of risk and miscalculation.

Therefore, as first objective of the market research could be considered the procurement and preparation of short- and long term, decision-relevant information. Hereby the information basis of the decision maker could be improved and the uncertainty reduced,[134] thus alleviating both of these problems

Another important role of the market research is the selection and evaluation of information. Nowadays, particularly with regard to consumer good markets a lot of data and information is being generated. The task of the market research could not be to gather all of the available information and just forward it, but rather to select, structure, prioritize and compress the information in accordance to the specific issue.[135]

Eventually the market research could also have an excitation function. In other words when the market researcher actively searches for information, which could represent opportunities or risks, or information which opens new possibilities to expand the company's strengths and reduce its weaknesses.[136] Opportunities could reveal themselves when latent and manifested needs of potential customers are identified, while risks could result from the consequences of an unsuccessful product market launch.[137]

2.3.1.2 Data collection methods

Within the market research, it could be distinguished between primary and secondary market research.[138] The main distinctive characteristics are the used data and the nature of the data collection.

In course of the **primary market research,** data is collected mainly by interviews, surveys and observations. This data could be referred as "original" data, as it has been gathered first hand for a specific problem. The traditional methods of the primary research encompass classical methods as surveys, observations, group discussions and creativity techniques and in most cases these techniques are rather time and financial cost consuming, although with the growing availability of internet connection

[133] Cf. Hammann, Erichson (2000), p. (25–27)
[134] Cf. A. Magerhans (2016), p. (4)
[135] Cf. Kühn, R./Kreuzer, M. (2006), p. (13)
[136] Cf. Krämer, A./Wilger, G. (1999), p. (13)
[137] Cf. R.Olbrich, D. Battenfeld, C. Buhr (2011), p. (9)
[138] Cf. A. Magerhans (2016), p. (63)

across the population and rising connection speeds, entirely new opportunities for primary research reveal themselves. To the internet-based methods count E-Mail-surveys, Web-surveys, Web-experiments and discussions and surveys in different news groups and forums. The passive online methods include click-measurements, online-observations, user tracking, cookie-analysis and eye tracking. [139]

Often, when a problem could be solved by using already available data alone, **secondary market research** can substitute the primary research.[140] The secondary market research is characterized by the gathering and using of already available data for the solution of a specific problem, which however was already collected for different purposes. Because the actual purpose and the original purpose of the gathered information may vary, within the secondary market research completely new connections and relations must be examined.[141] The main advantage of the secondary market research is that it could be completed without getting up from the desk. For this reason it is also referred as “desk research”. Besides the traditional sources of the secondary research (sales data, production data, official statistics, publications of different institutions, books and magazines, etc.), which can be divided in company intern and extern, in the recent years internet-based sources are becoming more and more popular. Online resources are usually very up to date, easily stored and globally retrievable.

2.3.2 Market variables

Alongside other market variables, the market potential counts to the helpful tools of the market analysis, which are used to quantitatively describe the market.[142] The next figure shows the hierarchical arrangement of these characteristics.

[139] Cf. A. Magerhans (2016), p. (68f.)
[140] Cf. R.Olbrich, D. Battenfeld, C. Buhr (2011), p. (67)
[141] Cf. A. Magerhans (2016), p. (63f.)
[142] Cf. M. Schürmann (2011), p. (66)

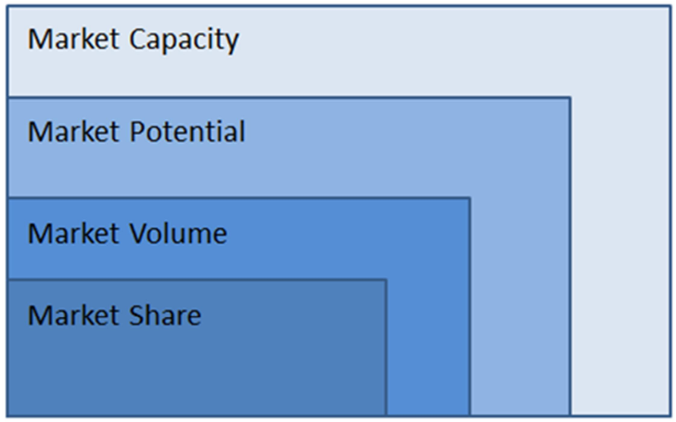

Figure 2-28: Market Variables[143]

All of the variables shown in Figure 2-28 refer to a clearly defined market at a specific time period. As it can be seen from the graph, the market capacity represents the total absorbing capacity of a market for a particular product although without considering the purchase power of the population.[144] The market potential on the other hand describes the estimated maximum revenue of a particular product on the market at a certain period, which requires knowledge and understanding of the market.[145] The market volume represents the actual turnover of a product that has been realized over a certain period of time, whilst the market share provides information about the turnover share a particular company has realized.[146]

2.3.3 Learning curves and cost estimation

The estimation of the production and operation (costs for maintenance) cost is a vital part of the project management. Already in the project preparation phase, e.g. during the feasibility study, an early cost assessment of the system is important for potential investors. These could carry a decisive role in the choice of development and production location and for the project start as a whole. In the concept and the decision phases, the contractor as well needs an accurate estimation of the costs, in order to assess the plant investment economic efficiency and enable a justified investment decision.[147]

[143] Own illustration based on M. Schürmann (2011), p. (66)
[144] Cf. M. Schürmann (2011), p. (66)
[145] Cf. H. Meffert,C. Burmann, M. Kirchgeorg (2012), p. (52)
[146] Cf. M. Schürmann (2011), p. (67)
[147] Cf. K Weber (2016), p. (453)

Equally as important however, is the ability to estimate how the system cost will decrease with the production volume and make a justified forecast when the Break Even Point will be reached. In other words that is the ability to tell, when a new technology close to market entry will reach a competitive state compared to the conventional, already approved technologies. For this reason, methods are needed, which with a minor input and within a limited accuracy tolerance could deliver usable results. This applies even more so, when the estimated future system costs and the derived economic efficiency contribute the most to the competitiveness of the product

One such method is the learning curve model. “It is used extensively in the industry as a tool for production planning and cost forecasting.”[148] The learning curve model was first introduced in the 1930s by T.P Wright (1936), who observed that direct labor costs of producing an airframe for an airplane declined with the accumulated number of airframes produced following the function given below:[149]

$$T_N = T_1 \times (N)^b \tag{10}$$

where T_N = Costs for the Nth unit

T_1 = Costs to produce the first unit

$b = {}^{(\log \text{of the learning rate})}\big/_{(\log 2)}$

= Slope of the learning curve

The learning curve is based on doubling of the production: when the production doubles, the time/cost per is reduced by the rate of the learning curve. Practitioners however, find it more beneficial to work with the graph (Figure 2-5) and to express the slope in percent – the slope being an indicator of the constant percentage reduction in an item’s cost.[150] For example a rate of 80% means that the production time of the second unit equals only 80% of the production time of the first one. The production time of the fourth equals 80% of the time of the second and so forth – in other words, every time the production quantity is doubled, the hours are reduced to 80% of what they were before.[151]

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[148] M. B. Lieberman (1984), p. (213)
[149] J.Heizer, B. Render, C. Munson (2014), p. (776)
[150] F. Dahlhaus, J. Roj (1967), p. (5)
[151] Cf. H. Degischer, S. Lüftl (2009), p. (378)

T.P. Wright concluded that regardless the time to build the first airplane, the learning curves applied to various types of air frames – jet fighters vs. passenger planes vs. bombers, which was confirmed by other airplane manufacturers as well.[152] The learning curve graph in Figure 2-29 shows the price or time per unit as a parameter that changes over a cumulated repetition of a task performed. From the graph it can be seen that the time/cost to produce a unit decreases with each additional unit, following a negative exponential curve in (a), although it is also obvious that with each additional unit the time/cost savings decrease. The log-log graph in (b) returns a straight line that is easier to extrapolate.

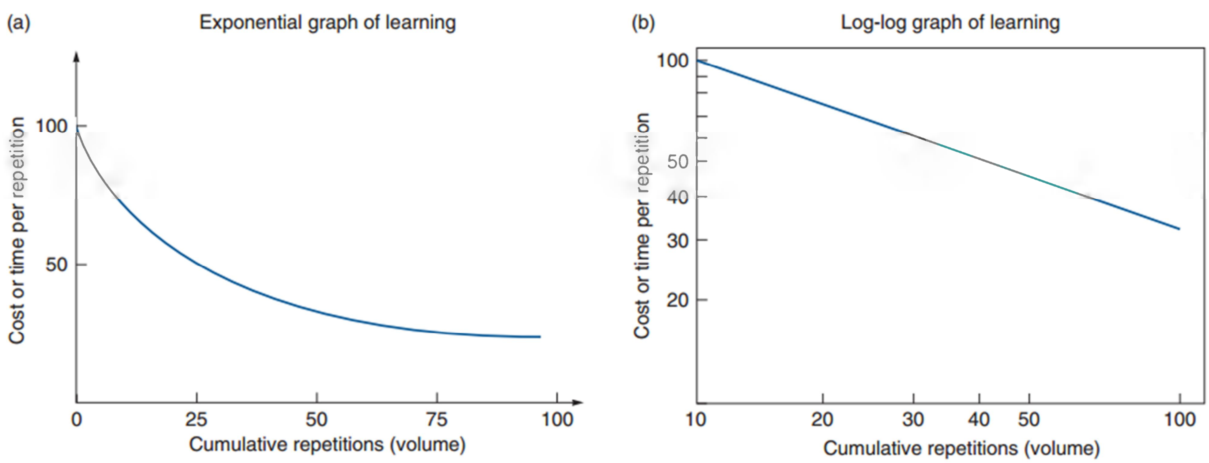

Figure 2-29: Learning curve graph[153]

During the 1950s and 1960s most of the research on this topic addressed the question, whether this learning principle could be applied to the manufacture of other products. Although some minor differences in the learning curves for different products were found, the model introduced by Wright received general confirmation.[154] The Table 2-4 below, shows how wide applicable the learning curve model could be. Different organizations and different products have different learning curves and the learning curve rate depends strongly on the quality of the management and the potential of the product. The learning curve rate and the cost are also interrelated, the lower the rate, the steeper the slope is and the faster the drop in the cost.[155]

[152] Cf. J.Heizer, B. Render, C. Munson (2014), p. (776)
[153] J.Heizer, B. Render, C. Munson (2014), p. (776)
[154] Cf. M. B. Lieberman (1984), p. (213)
[155] Cf. J.Heizer, B. Render, C. Munson (2014), p. (778)

Example	Improving Parameter	Cumulative Parameter	Learning-curve Slope (%)
1. Model-T Ford	Price	Units produced	86
2. Aircraft assembly	Direct labor hours per unit	Units produced	80
3. Equipment maintenance at GE	Average time to replace group of parts	Number of replacements	76
4. Steel production	Production worker labor-hours per unit produced	Units produced	79
5. Integrated circuits	Average price per unit	Units produced	72
6. Handheld calculator	Average factory selling price	Units produced	74
7. Disk memory drives	Average price per bit	Number of bits	76
8. Heart transplants	1-year death rates	Transplants completed	79

Table 2-4: Exemplary learning curve rates for different products and technologies[156]

As it can be seen from Table 2-4, the learning rates of different industries vary widely

In the mid-1960s the learning curve notion was generalized by the Boston Consulting Group (BCG), who called it the „experience curve“. It encompasses the behavior not only of the direct labor costs, but of all value added costs and prices such as capital, marketing, procurement and administrative costs as the cumulative volume or experience increase.[157] So the essential difference between the learning and experience curves is the extent of the included costs.

Sources of the experience curve effect

Now that evidence to the existence of the experience curve effect has been presented, the sources of this effect have to be examined.

In the most cases, the experience curve is the aggregate result of learning, technological advances and economies of scale and it is not easy to separate the contributions of each component, in part because the effect of learning is tightly connected to the scale effect.[158]

Learning incorporates the efficiency growth of all aspects of the workforce input, resulting from the practice and exercise of skill, ingenuity and the growing dexterity in

156 Own illustration based on J.Heizer, B. Render, C. Munson (2014), p. (778)
157 Cf. G. S. Day, D. B. Montgomery (1983), p. (44)
158 Cf. G. S. Day, D. B. Montgomery (1983), p. (48)

repetitive action.[159] Spence (1981), in his work focused on the competitive equilibria of the learning effect has found out that, when in a company a learning process takes place, part of the short-term marginal costs that may arise could be seen as an investment, which reduces production cost in the future.[160]

Technology advances also contribute strongly to the experience curve effect. The implementation of new technologies and processes such as complete process automation and the introduction of industrial robots, especially in capital intensive industries could be source of significant economies. Product and process standardization are also origins of the effect as with the effects achieved in the automobile industry by system and component modularization principle.[161]

Economies of scale represent another source of the experience curve effect. These scale effects are applicable in most investment cases and operation costs. Hardly ever has an increase in the output turned out an equal demand in capital investment or sales. Actually scale is promoter for other cost reduction actions by creating potential for volume discounts. Furthermore scale enables vertical integration and the division of labor, which itself further alleviates learning. [162]

The Cumulative Average and the Incremental Unit Model

The learning or experience curve concept is based on the assumption that if task are repeated over a longer period, organization will get better at them. There are two models that describe the learning curve effects - the original one, already mentioned was developed in 1936 by T. P. Wright and it is referred as the Cumulative Average Model or Wright's Model. Some years later, group of scientists of the Stanford University came up with a second model, which is referred as the Incremental Unit Cost Model or Crawford's Model.[163] While both models base on the power law formula, they work in a different way. The Cumulative Average Model looks at the learning effect as an occurrence, which affects the average production time for a sequence of units and with the growth of the sequence, the average time to produce a unit declines. The Incremental Unit Model on the other hand, considers the learning effect

[159] Cf. G. S. Day, D. B. Montgomery (1983), p. (46)
[160] Cf. M. B. Lieberman (1984), p. (213)
[161] Cf. G. S. Day, D. B. Montgomery (1983), p. (46-47)
[162] Cf. G. S. Day, D. B. Montgomery (1983), p. (47)
[163] Cf. J. R. Martin, p. (1)

as an occurrence, which affects each individual unit. According to this model each subsequent unit requires fewer production hours as the previous one.[164]

Wright's Cumulative Average Model

In the model introduced by T. P. Wright the function of the learning curve is defined in the following way:[165]

$$T_N = T_1 \times (N)^b \qquad (11)$$

where:

T_N: is the average hours (costs) for a single unit in the lot

T_1: is the time (cost) required to produce the first unit

N : is the number of units produced in the lot

b : is the slope of the learning curve

= log of the learning rate/log of 2

For a learning curve with 80% rate, the slope is calculated as follows:

$$b = \log(0{,}8)/\log(2) = -0{,}32196 \qquad (12)$$

In an example, if the first unit requires 100 hours to be produced and the direct labor costs equal 20$ per hour, the function would look like as:

$$T_N = T_1 \times (N)^b = 100 \times (N)^{-0.322} \qquad (13)$$

With the formula above, we would be able to predict the average time for the production of a unit in the lot, but in order to calculate the total time needed for all the units from the lot, both sides of the equation must be multiplied with *N:*

[164] Cf. E. Stump, p. (23)
[165] J.Heizer, B. Render, C. Munson (2014), p. (776)

$$T_{1,N} = T_N \times N = T_1 \times (N)^b \times N = T_1 \times (N)^{b+1} = T_1 \times (N)^{0,678} \quad (14)$$

The average labor hours per unit and the cumulative total cost and hours for the production of the first eight units, which are calculated using the equations carried out above, can be seen in Table 2-5 below:

Labor Cost per Hour ***C [$/h]***	Number of Units produced ***N [units]***	Average Labor Hours per unit ***T_N [h/unit]***	Cumulative Total Labor Hours ***$T_{1,N}$[h] = T_N x N***	Average Labor Costs per unit ***T_N x N [$/unit]***	Cumulative Total Labor Costs ***$T_{1,N}$ x N [$]***
20	1	100	100	2000	2000
	2	80	160	1600	3200
	3	70	211	1404	4212
	4	64	256	1280	5119
	5	60	298	1191	5956
	6	56	337	1123	6739
	7	53	374	1069	7482
	8	51	410	1024	8191

Table 2-5: Example of the Cumulative Average Model for a learning rate of 80%[166]

As it can be seen from the third column, when the production doubles each following value decreases with 20% (values marked red), or the subsequent value amounts to only 80% of the previous one. On the other hand, the values of the cumulative total columns four and six grow with a rate, which is equal to twice the learning rate or 160%. As both the growth and the decrease rate do not change its value, it is very easy to create tables for the doubled unit numbers. For the unit numbers in between however, the equations from above are needed.

Crawford's Incremental Unit Model and the midpoint concept

The equation of the learning curve used in the Crawford's Model is as follows:[167]

$$T_N = T_1 \times (N)^b \quad (15)$$

where:

[166] Own Table
[167] J. R. Martin, p. (1)

T_N: is the hours (cost) for the *Nth* unit of production

T_1: is the time (cost) required to produce the first unit

N : is the number of units produced

b : is the slope of the learning curve

= log of the learning rate/log of 2

If we use the same example with the 80% learning rate from before, to calculate the total hours needed for the production of all units, we would need to sum up all the terms in the lot:[168]

$$T_{1,N} = T_1 \times [M^b + (M+1)^b + (M+2)^b + \cdots + N^b] \qquad (16)$$

Since for the use of this formula, the entire lot should be taken term by term, a very good approximation formula was developed:[169]

$$T_{1,N} = [T_1/(1+b)] \times [(N+0{,}5)^{1+b} - (1-0{,}5)^{1+b}] \qquad (17)$$

The incremental unit labor hours per unit and the total cost and hours for the production of the first eight units, which are calculated using the equations carried out above, can be seen in Table 2-6 below. As it can be seen from the third and fifth column, each time the production doubles, the hours and the costs respectively decrease with 20% (values marked red). The total hours and costs for the production of all units however – columns four and six, are calculated by adding the cost of every single unit. For these reason the total hours and costs are growing at a variable rate and it also shows that the total hours and costs calculated with the Cumulative and the Incremental Models are not exactly compatible, when based on the same learning rate.

[168] E. Stump, p. (12f.)
[169] Ibidem

Labor Cost per Hour *C [$/h]*	Number of Units produced *N [units]*	Incremental Unit Labor Hours *T N [h]*	Total Labor Hours *T 1,N [h] = T N + T N+1*	Incremental Unit Labor Costs *T N x N [$]*	Total Labor Costs *T 1,N x N [$]*
20	1	100	100	2000	2000
	2	80	180	1600	3600
	3	70	250	1404	5004
	4	64	314	1280	6284
	5	60	374	1191	7475
	6	56	430	1123	8598
	7	53	483	1069	9667
	8	51	535	1024	10691

Table 2-6: Example of the Incremental Unit Model for a learning rate of 80%[170]

The midpoint concept of the Crawford model gives an interesting opportunity to predict an "average" price per unit in a lot, instead of estimating the price for every single unit in it. In this case, the experience curve has the following function:

$$T_K = T_1 \times K^b \tag{18}$$

where,

T_K: is the incremental unit time of the lot midpoint unit

K: is the algebraic midpoint of a production lot

In the equation above, *K* is called the "midpoint unit", although it is unlikely for it to ever be halfway through the lot. What the equation actually describes is the average number of production hours in the lot. If the number of units in the lot is designated with the letter Q:

$$Q = N - M + 1 \tag{19}$$

Then the production costs for the complete lot can be easily calculated by multiplying *Q* by the average number of production hours in the lot:

$$T_{1,N} = T_K \times Q \tag{20}$$

170 Own Table

$$T_{1,N} = T_1 \times K^b \times Q \quad (21)$$

And from here, we can calculate the midpoint unit *K,* which results in:[171]

$$K = (T_{1,N}/(T_1 \times Q))^{1/b} \quad (22)$$

And with the formula for $T_{1,N}$, *K* results in:[172]

$$K = ([(N + 0{,}5)^{1+b} - (M - 0{,}5)^{1+b}]/[(1 + b)(Q)])^{1/b} \quad (23)$$

where: N: is the last unit in the lot

M: is the first unit in the lot

An example calculation for different lot sizes and 100 hours required for the production of the first unit can be seen in the Table 2-7:

Labor Cost per Hour ***C [$/h]***	Number of units in the lot ***N [unit]***	Midpoint Unit ***K [unit]***	Average Labor Hours To Produce 1 Unit ***T_K [h/unit]***	Average Costs To Produce 1 Unit ***T_K x C [$]***	Total Labor Hours ***T_1,N [h]***	Total Labor Cost ***T_1,N x C [$]***
30	100	32	33	980	3267	98024
	250	78	25	738	6149	184455
	1000	304	16	476	15867	476011

Table 2-7: Example of the Crawford's Model for a learning rate of 80%[173]

As it can be seen from the Table 2-2, independent of the lot size the midpoint unit lays roughly one third of the way through the lot. This estimation is more or less valid for all lots that start at unit one, however it does not apply to batches which do not begin at unit one.

[171] Cf. E. Stump, p. (15)
[172] Ibidem
[173] Own Table

2.3.4 Total Cost of Ownership

As the national economies are becoming ever more internationally interdependent, the competition for the European business intensifies, thus further complicating the economic framework in which local companies operate. For this reason, firms that are somehow directly or indirectly affected by the international product trade, have to find out for themselves, which strategies open up due to the market globalization and would actually allow them to remain competitive under the more challenging conditions.[174]

The development from the recent years has shown that in order to improve their competitive position, more and more European companies have decided as a part of their strategy to focus their efforts on their core competences, instead of working on their agility and offering different cost benefits. Therefore many non-essential processes have been outsourced to countries with lower labor costs. The associated declining production depth however, led inevitably to a huge increase in the purchased part percentage as part of the total company costs.[175] For example in 2004, the purchased items in manufacturing firms accounted for more than 60% of the total costs as well as for more than 80% in wholesale companies, making the efficient purchasing process an essential part of the company's overall success and prosperity.[176] Thereby it is clear, that cost savings in the purchasing process could have dramatic effect on the company's profitability.[177]

The lowest product acquisition price however is no guarantee, that exactly this product would have the lowest costs over its entire life cycle, on the contrary follow-up costs surpass on many occasions the actual acquisition costs.[178] The lack of knowledge, which often results in poor decisions, is likely to hurt the firm's profitability, pricing decisions and the overall competitiveness.[179] For this reason methods were needed, which could with sufficient certainty determine the total cost of a system over its active usage period. \

One such methodology is the Total Cost of Ownership (TCO), which originated from the USA and is aiming to establish the full amount of costs that could occur over the lifecycle of a product or a service that a company has decided to acquire. In this way, it enables purchase managers to reach a justified decision by providing them a complete

[174] Cf. M. Hütter (2008), p. (17)
[175] Cf. S. Krämer (2007), p. (2f.)
[176] Cf. K. Geißdörfer (2009), p. (1)
[177] Cf. S. Krämer (2007), p. (2)
[178] Cf. K. Geißdörfer (2009), p. (1)
[179] Cf. L. M. Ellram (1995), p. (4)

and objective evaluation of the different product and supplier alternatives. This idea, which besides the acquisition costs evaluates also other possible cost that could occur during a product lifecycle is not new and has its origins in the late 1920s.[180] However the actual driving force behind the growing popularity of the TCO concept was the lack of resources and the continuously rising salary levels, maintenance costs and prices of commodities such as energy and raw materials.[181]

With the cooperating of different companies Ellram (1995) was able to identify the main practical applications of the TCO concept. Besides the supplier selection function, other primary reasons for the TCO adoption included the measurement and evaluation of ongoing supplier performance and also to impel major process changes.[182]

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180 Cf. S. Krämer (2007), p. (5)
181 Cf. K. Geißdörfer (2009), p. (2)
182 Cf. L. M. Ellram (1995), p. (8)

3 Application analysis and market potential estimation

After getting familiar with the theoretical background, the following chapter represents the first practical section of this thesis. It contains an analysis of the possible applications and operation scenarios of the SOFC CCHP system followed by an extensive research of the European power and cooling market with the goal of estimating the market potential of the SOFC CCHP system.

3.1 Stationary use of Fuel Cells

As already mentioned in section 1.2), fuel cells can be used in a wide range of stationary applications that can be divided in three main categories: large scale units configured for prime power alone or also in CHP configuration, units used as a backup solution in uninterruptable power supply systems (UPS) and smaller micro-CHP units for residential applications.[183] In these stationary appliances, four main types of fuel cells are being applied, making up for the majority of installations today including the MCFCs, SOFCs, PEMFCs and the PAFCs.[184]

The main type of fuel cell used in the large-scale power generation sector is the MCFCs with the SOFCs technology undergoing significant progress in the past few years.[185] These fuel cell systems are available in the range of 10s of kW to almost 100 MW in large stationary power plants, like in South Korea where in 2014 the Gyeonggi Green Energy Park with 59 MW_e of installed capacity came to be the largest fuel cell park in the world. That system is made of 21 fuel cell modules, which provide uninterrupted base load to the city of Seoul, as well as heat for the city's district heating system. [186]

In the off-grid and back-up power sector, fuel cells have some major advantages over the conventional generators and battery banks. Fuel cell systems offer reliable continuous power supply over extended periods, have negligibly low maintenance costs, have small footprint and can be installed in sensitive environments because of their low noise and emission levels. For example fuel cells could deliver reliable power to telecommunications networks located in remote areas, thus avoiding the cost of extending the present electric grid and balancing the higher cost per kw-capacity.[187]

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[183] Cf. Fuel Cell Today (2011), p.(5)
[184] Cf. C. Jackson (2016), p.(25)
[185] Cf. A. Hawkes, D. Brett (2013), p. (2)
[186] Cf. C. Jackson (2016), p. (2)
[187] Cf. A. Hawkes, D. Brett (2013), p. (3)

For the first time in 2012, SOFC and PEMFC micro-CHP systems in the range of 0.7-0.75 kW_e and overall efficiencies of 80-95 % outsold fossil fuel based micro-CHP systems taking 64 % of the global market with approximately 28000 units.[188] By 2015 around 140.000 micro-CHP systems have been installed in course of the Enefarm program in Japan and the Ministry of Economy, Trade and Industry (METI) revealed its plan this number to reach 1.4 million units by 2020 and 5.3 million units by 2030.[189-190] In Europe the ene.field initiative within 11 key EU member states, started by spreading out 1000 micro-CHP units, forecasting the installed units to reach 50000 by the year 2020.[191] Both initiatives show that there is strong support for the establishment of the fuel cell micro-CHP technology with the goal to demonstrate the system maturity and to drive down the system cost by co-funding installations in the private sector, thus commercializing the technology.

3.2 Requirements for an economically profitable application of the SOFC CCHP System

- Constant power consumption must be present.
- Relatively constant cooling demand must be present.
- Relatively constant heating demand must be present.
- The application field must be in the range of 20-100 kW_{el} electric and 5-20 kW_{Cool} cooling power capacities.

In compliance with the above stated criteria and considering the different possibilities stated in the previous section 3.1), different application scenarios start to emerge from the different sectors. From the residential sector, the building type that fits best the above mentioned criteria is the multi-family apartment block, whereas the non-residential or commercial sector is represented by supermarkets, office buildings and hotels, which are attractive due to their longer operating hours. However, data centers and telecom base station seem to be the best possible option as they operate year round without interruptions thus offering the highest grade of utilization.

[188] Cf. C. Jackson (2016), p. (3)
[189] Cf. Fuel Cell Today (2015), p. (4)
[190] Cf. C. Jackson (2016), p. (3)
[191] Ibidem

3.3 Analysis of the operation scenarios of the different applications

By means of secondary market research using different data bases, statistics and surveys, the amount of the above mentioned applications for Austria and the EU total could be approximated. Their numbers are displayed in the following Table 3-1.

	Austria [Amount]	EU-28 [Amount]
Households in Multi-family buildings	1.971.130[192]	105.313.720[193]
Office buildings	35.420[194]	3.253.260[195]
Hotels	13.300[196]	132.400[197]
Supermarkets	2.715[198]	94.042[199]
Data centers	17[200]	1.113[201]
Telecom base stations	17.952[202]	728.000[203]

Table 3-1: Amount of the possible applications in Austria as well as in the EU-28[204]

3.3.1 Multi-family buildings

Multi-family buildings consist of many single family dwellings, which presume a relatively constant energy demand. In Austria in 2014 there were 1,971 million dwellings spread across 246.850[205] multi-family buildings with more than three dwellings each and in the EU-28 the number of such households sums up to over 105 million. The average electricity consumption per household in Europe has been estimated at 3500 kWh/y, which results in a total electricity consumption of about 6899

[192] EU Building Database, https://ec.europa.eu/energy/en/eu-buildings-database - Date of access: 18.5.2017
[193] Ibidem
[194] Statistik Austria, http://www.statistik.at – Date of access: 18.5.2017
[195] EU Building Database, https://ec.europa.eu/energy/en/eu-buildings-database - Date of access: 18.5.2017
[196] Statistik Austria, http://www.statistik.at – Date of access: 18.5.2017
[197] Otus & Co, http://www.otusco.com/Otus%20Hotel%20Analyst%20Size%20and%20Structure%201.pdf – Date of access: 18.5.2017
[198] Nielsen, http://www.nielsen.com/content/dam/nielsenglobal/eu/nielseninsights/pdfs/Nielsen_AT_Basisdaten_2013.pdf, Date of access: 18.5.2017
[199] GAIN, https://gain.fas.usda.gov/Pages/Default.aspx - Date of access: 18.5.2017
[200] http://www.datacentermap.com/western-europe/ - Date of access: 18.5.2017
[201] Ibidem
[202] http://www.fmk.at/mobilfunktechnik/zahlen-und-fakten/mobilfunkstationen-in-osterreich/ - Date of access:18.5.2017
[203] Analysys Mason, http://www.analysysmason.com/Research/Content/Reports/Base-station-deployments-forecast-May2012-RDTN0/ - Date of access:18.5.2017
[204] Own table
[205] Statistik Austria, http://www.statistik.at - Date of access:18.5.2017

GWh per year.[206] Analogous calculation for the EU-28 results in a total electricity consumption of about 368598 GWh per year. The heating demand per dwelling in multi-family buildings in Austria was also available in the EU Building Database and in 2014 it came to 13539 kWh per year whereas the EU-28 yearly average added up to 11118 kWh.[207] Unfortunately there was no separate data available on the cooling demands of multi-family buildings, which could originate from the fact that many households rely on small single room electricity driven cooling devices, which makes the separate collection of their electrical consumption very difficult. For this reason it can be assumed that the energy used for cooling is already included in the electrical demand of these households.

	Austria	EU-28
Households in multi-family buildings [Amount]	1.971.130	105.313.720
Electricity demand [GWh]	6.899	368.598
Cooling demand [GWh]	-	-
Heating demand [GWh]	26.687[208]	1.071.515[209]
28 kW_{el} SOFC CCHP Module [Amount]	28.127	1.502.764

Table 3-2: Heating, cooling and electricity demand in multi-family buildings in Europe[210]

From the available data from the Table 3-2 above follow the respective heating and electricity demand in Austria and for the EU-28 as well as an estimate of the market capacity of the SOFC CCHP unit. Considering the fact that the system is first and foremost an electrical generator the calculated amount of SOFC CCHP systems is based on the electrical demand.

3.3.2 Office Buildings

Office building typically have diverse electrical equipment at their disposal, which combined with the longer operating hours – normally between 7 am and 20 pm, results in more significant base load consumption. Besides the external heat loads, the heat produced by the electrical equipment and the lighting systems is a further cause for the higher comfort cooling demand. In 2014 the number of office buildings in Austria

[206] OVO Energy, https://www.ovoenergy.com/guides/energy-guides/how-much-electricity-does-a-home-use.html – Date of access: 10.10.2017
[207] EU Building Database, https://ec.europa.eu/energy/en/eu-buildings-database - Date of access: 18.5.2017
[208] Ibidem
[209] Ibidem
[210] Own table

amounted 35.420, while the number for the EU-28 comes to 3.253.260 buildings. Both of these figures include buildings from the private as well as the public sector. According to IWU Darmstadt, the average value for cooling in a standard office building comes to 31 kWh/m^2 yearly, whereas the values for heating and electricity average respectively to 74 kWh/m^2 and 130 kWh/m^2 per year.[211] The resulting estimated numbers of the SOFC CCHP modules can be seen in the following table.

	Austria	EU-28
Office Buildings [Amount]	35.420	3.253.260
Total floor area [m^2]	46.000.000[212]	2050.000.000[213]
Electricity demand [GWh]	5.985	266.562
Cooling demand [GWh]	1.427	63.565
Heating demand [GWh]	3.407	151.736
28 kW$_{el}$ SOFC CCHP Module [Amount]	24.402	1.086.768

Table 3-3: Heating, cooling and electricity demand in office buildings in Europe[214]

3.3.3 Hotels

The hotel sector is characterized by the discontinuity of its operation due the continuous arrival and departure of its guests. For this reason, the most appropriate method to determine the energy demand would be to use the actual number of nights spent. In 2014 in Austria there were 87 million overnight stays registered, while in EU-28 they add up to 1.801 million[215]. This methodology however, restricts us from distinguishing the categorization of the hotels, therefore for the calculation of the electrical, heating and cooling demands will be used values from the mid-market sector, being the largest one in Europe with 45% of the total room number.[216] On average the electricity demand in this sector amounts 23 kWh per night and 40 kWh for heating.[217] As in the residential sector, no separate data was available on the cooling demand. Table 3-5 shows the approximated energy demands as well as the market capacity of the SOFC CCHP module in this market sector.

211 Institut Wohnen und Umwelt Darmstadt, http://www.iwu.de/fileadmin/user_upload/dateien/energie/verwaltungsbau.pdf - Date of access: 22.5.2017
212 EU Building Database, https://ec.europa.eu/energy/en/eu-buildings-database - Date of access: 18.5.2017
213 Ibidem
214 Own table
215 Eurostat, http://ec.europa.eu/eurostat/statistics-explained/index.php/Tourism_statistics_-_annual_results_for_the_accommodation_sector - Date of access: 22.5.2017
216 Otus & Co, http://www.otusco.com/Otus%20Hotel%20Analyst%20Size%20and%20Structure%201.pdf – Date of access: 22.5.2017
217 ÖGUT, Kennzahlen zum Energieverbrauch in Dienstleistungsgebäuden (2011), p. (16)

	Austria	EU 28
Nights spent [Amount]	87.000.000	1.801.000.000
Electricity demand [GWh]	1309	27.009
Cooling demand [GWh]	-	-
Heating demand [GWh]	3.256	67.161
28 kW_{el} SOFC CCHP Module [Amount]	5.338	110.113

Table 3-4: Heating, cooling and electricity demand in hotels in Europe[218]

3.3.4 Supermarkets

There is no exact definition of the term supermarket, but these can be characterized as self-serve grocery stores that also offer a variety of household merchandize. Up to 2014 in Austria there were 2.715 supermarkets and 94.042 such stores in the EU-28.[219] In the past few years there, due to the lifestyle change and the related growth in the consumption of semi-finished products, a transformation in the supermarket has been observed that has led to an increase in the number of refrigeration units per store. This fact contributed to the increased electric power consumption of these stores.[220] According to the German Bundesinstitut für Bau-, Stadt- und Raumforschung, the electric demand for stores >300 m^2 amounts to 375 kWh/m^2 and the head demand accounts for 135 kWh/m^2 per year.[221] As in previous applications, unfortunately no data was available that would separately record the cooling demand of supermarkets.

	Austria	EU-28
Supermarkets [Amount]	2.715[222]	94.042[223]
Electricity demand [GWh]	1.018	35.266
Cooling demand [GWh]	-	-
Heating demand [GWh]	367	12.696
28 kW_{el} SOFC CCHP Module [Amount]	4.151	143.778

Table 3-5: Heating, cooling and electricity demand in supermarkets in Europe[224]

218 Own table
219 Nielsen, http://www.nielsen.com/content/dam/nielsenglobal/eu/nielseninsights/pdfs/Nielsen_AT_Basisdaten_2013.pdf, Date of access: 18.5.2017
220 Ibidem
221 BBSR (2009), http://www.bbsr.bund.de/BBSR/DE/Veroeffentlichungen/BBSROnline/2009/DL_ON092009.pdf?__blob=publicationFile&v=2 – Date of access:22.5.2017
222 Nielsen, http://www.nielsen.com/content/dam/nielsenglobal/eu/nielseninsights/pdfs/Nielsen_AT_Basisdaten_2013.pdf, Date of access: 18.5.2017
223 GAIN, https://gain.fas.usda.gov/Pages/Default.aspx - Date of access: 18.5.2017
224 Own table

3.3.5 Data Centers

Data centers can be described as high-density computing facilities, used to accommodate computer servers that can store or process large amounts of information.[225] With the growing implementation of internet into everyday life – e.g. internet of things, etc. grows also the amount of data to be processed and therefore the number of data centers.[226] In 2017 there are 17 data centers across Austria and 1.113 in the EU-28.[227] As these facilities are operational 24 hours a day, they consume vast amounts of energy. Moreover "for every watt of power consumed in the computing equipment, an additional 0.5 to 1W of power is required to operate the cooling system itself".[228] A study by the Borderstep Institute has shown that the annual data center energy consumption in Europe has grown 20% in the period from 2010 – 2015 and has reached a total of 55 TWh[229] that also includes an estimated 35% share of the energy used for cooling purposes. With the known power consumption and the number of data centers in the EU-28, the average power consumption per data center can be estimated at 49 GWh per year. With this value the electricity demand of the Austrian data centers is estimated at 840 GWh per year.

	Austria	EU-28
Data Centers [Amount]	17	1.113
Electricity demand [GWh]	840	55.000
Cooling demand [GWh]	294	19.250
Heating demand [GWh]	-	-
28 kW_{el} SOFC CCHP Module [Amount]	3425	224.234

Table 3-6: Heating, cooling and electricity demand in data centers in Europe[230]

3.3.6 Telecom Base Stations

Mobile base stations (BS) are the pillars of the telecommunication system today, as they are the devices that transmit telephone calls and internet data between mobile phones and thus form the mobile network. As with other technical equipment, base stations also have their limits and can handle a certain amount of calls or data. With the market launch of the smartphone telecommunication companies had to cope with

[225] Cf. J. Koomey (2011), p. (5)
[226] Cf. S. Mittal (2014), p.(1)
[227] http://www.datacentermap.com/western-europe/ - Date of access:18.5.2017
[228] S. Mittal (2014), p.(2)
[229] Cf. Borderstep Institute (2015), https://www.borderstep.de/wp-content/uploads/2015/01/Borderstep_Energy_Consumption_2015_Data_Centers_16_12_2015.pdf - Date of access:23.5.2017
[230] Own table

the related growth of mobile data by increasing the bandwidth of the existing base stations and also the number of base stations as a total. A study on “Measurement and Modeling of Base Station Power under Real Traffic Loads” revealed that base stations are the biggest electricity consumer in a cellular networks and that a single base stations consumes on average 5.400 kWh of electricity per year, out of which 16% are used by the cooling system .[231] With the data from Table 3-7 results the estimated SOFC CCHP system capacity.

	Austria	EU 28
Base Stations [Amount]	18.000[232]	728.000[233]
Electricity demand [GWh]	1.163	47.174
Cooling demand [GWh]	186	7.548
Heating demand [GWh]	-	-
28 kW_{el} SOFC CCHP Module [Amount]	4.743	192.329

Table 3-7: Heating, cooling and electricity demand in telecom base stations in Europe[234]

3.4 European electrical- and cooling power market

In order to develop a better understanding of the electric and cooling power demand, the market of the reference power and cooling generation systems with the respective market shares in accordance to the different capacity segments was also investigated. The actual market sales data will give a far more realistic picture and thus serve us further with the estimation of a plausible market potential of the SOFC CCHP system.

3.4.1 Electrical power generation

At present, the electric power in Europe is generated in power plants as a primary or secondary product, whereas different mix of fuels is used for its production. [235] Typically it could be differentiated between gross and net production. The first term describes the total amount of energy produced by the power plants, while the net production describes the electric power amount left that could be distributed to the final customers through the transmission and electric grids, where it is being used for

231 J. Lorincz, T. Garma, G. Petrovic (2012), p. (19)
232 http://www.fmk.at/mobilfunktechnik/zahlen-und-fakten/mobilfunkstationen-in-osterreich/ - Date of access:18.5.2017
233 Analysys Mason, http://www.analysysmason.com/Research/Content/Reports/Base-station-deployments-forecast-May2012-RDTN0/ - Date of access:18.5.2017
234 Own table
235 Cf. Eurostat, http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview - Date of access: 23.02.2017

different purposes. The difference between gross and net production is in the amount of energy, which is being consumed internally by the power plants themselves. The total net electricity generation in the EU-28 reached 3.03 million GWh in 2014 and it was the fourth consecutive output fall since 2011.[236] At this rate it was 5.7% lower than the peak value in 2008 (3.22 million GWh). Among the EU-28 Member States, Germany had the highest level of net electricity generation in 2014 with 19.5% of the total, followed by France and the UK, the other two states with double digit percentage, respectively 17.8% and 10.6%.[237]

The different technologies used and their share in the generated electricity in 2014 can be seen in the Figure 3-1 below.

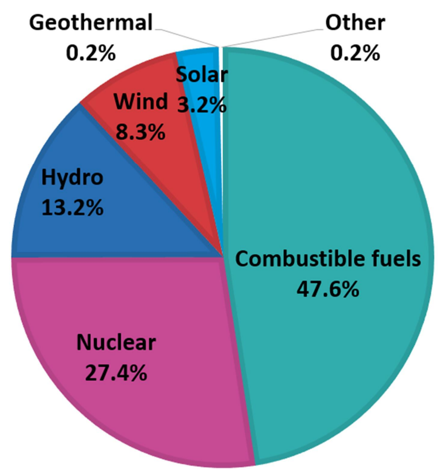

Figure 3-1: Net electricity generation in the EU-28[238]

At first place with 47.6% came the electricity produced by power plants using combustible fuels (such as coil, natural gas and oil). Almost twice as little came from nuclear plants with 27.4% and on third place with almost a quarter of the total are the renewable energy sources with 24.9%. While compared to the conventional technologies, the percentage of renewable energy seems to be rather small, but in reality it was the only group with a significant growth in the past decade, as it can be seen from Figure 3-2. In the period from 2004 to 2014 the amount of energy coming from renewable sources has almost doubled in size reaching 900 TWh total, representing 25% of the net consumption. On the other hand the energy produced by

[236] Cf. Eurostat (2016), http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview - Date of access: 23.02.2017
[237] Ibidem
[238] Eurostat (2014), http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview

combustible fuels experienced a significant drop from 55:9 % to 47.6 % in the period between 2004 and 2014. In the same period the hydropower energy sustained its share of 12 % of the total consumption, the power produced by wind turbines has tripled reaching 7 % and the one from biomass has doubled in size, rising to 4.3 %.[239]

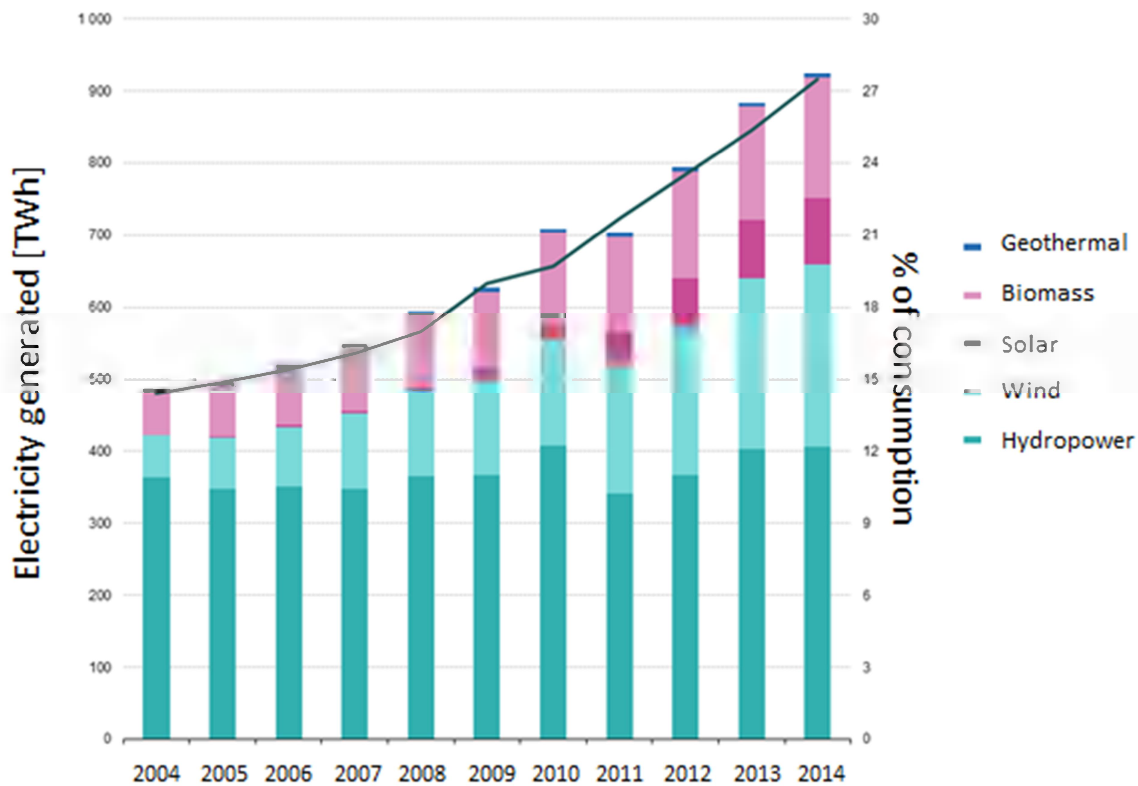

Figure 3-2: Development of the electric power generated by renewable energy sources[240]

The next Figure 3-3 shows the development of the renewable energy sources as a percentage of the total installed power generation capacities. further acknowledgement of the growing importance of the renewable energy sources. In 2016 the share of renewable's as a percentage from the total new installed power generation capacities has reached almost 90 % of all installations and as of 2010 it represents a growing trend.

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239 Cf. Eurostat (2016), http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview - Date of access: 23.02.2017

240 Eurostat (2016), http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview - Date of access: 23.02.2017

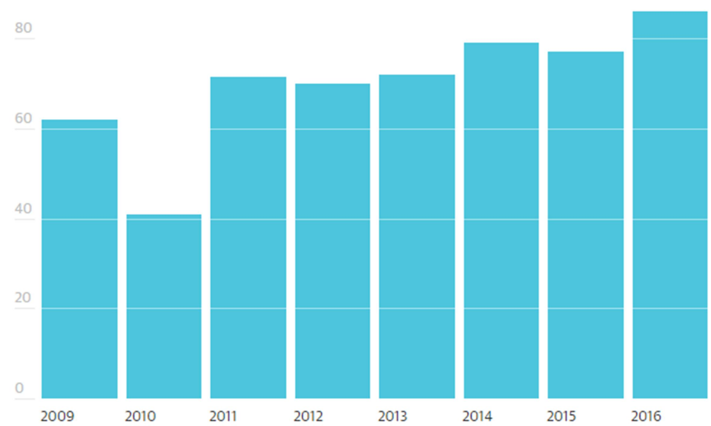

Figure 3-3: Renewables percentage share from the EU installed power generation capacities[241]

The development shown in Figure 3-3 sends a clear message that in the years to come the high percentage share of the renewable energies is expected to be sustained and even to grow further. From this can be concluded that the renewables would play an even more decisive role in the future energy supply the European Union.

This conclusion complies with the targets set in the European "Energy Roadmap 2050" or the Roadmap to a low carbon economy of the EU. In 2011 the European Union has decided upon an ambitious long-term goal to reduce the greenhouse gases by 80-95% below 1990 levels, by 2050 and the Roadmap points the way of how to get there. The Roadmap evaluates the transition possibilities of the energy system, so that while still retaining the high levels of supply security and competitiveness the systems will however achieve the greenhouse gas reduction goals.[242]

To ensure the low carbon transformation of the energy system, some key milestones were set:[243]

- **The 2020 Energy strategy**: By 2020, the aim is to reduce gas emissions by at least 20% compared to 1990 levels, increase the renewable energy share to at least 20% of the total consumption and achieve energy savings of at least 20%.

241 The Guardian, https://www.theguardian.com/environment/2017/feb/09/new-energy-europe-renewable-sources-2016 - Date of access: 11.5.2017

242 Cf. European Commission (2011), https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy - Date of access:10.5.2017

243 Cf. European Commission , https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union – Date of access: 15.10.2017

- **The 2030 Energy strategy**: By 2030, the gas emissions should be cut down by at least 40% compared to 1990 levels, the renewable energy consumption should amount at least 27% and energy savings should reach at least 27%.
- **The 2050 Energy strategy**: By 2050, the ultimate goal is to reach gas emissions reduction of 80-95% compared to the levels of 1990.

The costs for reaching the goals set in the strategy does not differ significantly from the price that the EU needs to pay in order to replace some parts of its aging energy infrastructure, however scenarios from the "Roadmap for moving to a competitive low-carbon economy in 2050" show that if energy investments in low-carbon technologies are postponed, they would cost much more on the long run.[244] All scenarios show also a conversion to a future low carbon energy system based on lower fuel costs but higher initial infrastructure investments.[245] With the Energy Roadmap 2050, the EU sends a strong signal to the market, encouraging private investments in low-carbon technologies. To these technologies belong in particular: [246]

- The renewable energy sources – hydro-, wind-, solar-, geothermal- and biomass energy
- Nuclear energy
- Highly efficient CHP plants

3.4.2 Cooling power generation

The European cooling sector nowadays, presents an interesting blend regarding its technologies. On the one hand, a strong concatenation exists between the cooling and the electricity sector as comfort cooling is produced mainly by electricity driven machines (e.g. vapor compression method), on the other hand there is an interlinkage between cooling and heating as well. An example of this is the heat-driven absorption chiller technology, discussed in section 2.1.5). Up to date however, most of the European market is ruled by electric cooling machines. Cooling in that case is supplied by electric driven devices, which remove heat/moisture from the air using individual or also central air-conditioning and ventilation devices.[247]

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[244] Cf. European Commission (2011), p.(2), http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0885&from=en – Date of access:11.5.2017

[245] Cf. European Commission (2011), p.(5) http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A52011DC0885 – Date of access:15.3.2017

[246] Cf. European Commission, 2030 Energy Strategy, Source: https://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy - Date of access: 23.2.2017

[247] Cf. European Commission (2016), p.(35)

Choosing an Air-Conditioning System

After discussing the different types of air-conditioning systems in chapter 2.2.1), now it is also possible to differentiate between them. However to understand how the choice for a certain system type is made requires also an understanding of the different factors which affect the selection process. Generally speaking, every building can be seen as a unique project because of the different functional requirements, occupancy pattern and criteria of usage. The geographical location of the building, the indoor requirements, the building materials, the ambient conditions, the noise and environmental issues are all factors that should be taken into consideration.[248] Understanding this process of selection will bring us further to identifying the possible applications of the SOFC CCHP unit.

Available space

The air conditioning system is a vital part of the modern building. For this reason in new constructions it is integrated in the early stages of the building design and therefore space is normally not considered a problem that could set limitations to the choice of air conditioning system. However, on some occasions space can be seen as a constraint. This is the case when existing buildings undergo significant refurbishment and a new cooling installation must be integrated into the existing building structure or when single components of an existing but old air conditioning system are being replaced, while still trying to utilize the rest of the system.

Cooling capacity and size of the conditioned area

A crucial factor for the successful implementation of an air conditioning system is the correct calculation of the cooling/heating loads. If the system is not dimensioned appropriately and it is too small or respectively too big for the current application it could have a huge effect on to the building's micro climate and thus affect the working environment. As it can be seen from Table 3-8, some systems like the split systems and the mini chillers are designed for smaller applications such as the residential and light commercial sectors. In the lower capacity segment, these systems represent the possible competitors for the SOFC CCHP unit. Other systems like the VRF, the Rooftops and the Chillers are more suitable for commercial applications. However, when the demand lies above 150 kW, the chillers are the only system that can deliver such cooling capacity.

[248] Cf. A. Bhatia (2012), p. (2)

Cooling Technology	System Type	Cooling Capacity
Movable ACs	Air Conditioner (DX System)	1,5 -8 kW
Single Splits	Air Conditioner (DX System)	2 - 15 kW [249] / 2 – 12,5 kW [250] / 2,5 - 6 kW [251]
Multi Splits	Air Conditioner (DX System)	5 - 15 kW [248] / 2,4 - 15 kW [250]
Ducted Splits	Air Conditioner (DX System)	5 - 80 kW [248]
VRF	Air Conditioner (DX System)	10 - 150 kW [248] / 11.2 - 136 kW [249] / 12,1 - 150 kW [250]
Rooftops	Air Conditioner (DX System)	15 - 150 kW [248] / 20 - 52 kW [249] / 27 - 110 kW [250] / 17-70 kW [252]
Mini chillers	Chiller-based (Chilled water System)	5,3 – 17 kW air cooled [251] / 5 – 16 kW [252]
Chillers	Chiller-based (Chilled water System)	20 kW - 2 MW [253] / 39,2 kW – 17,6 MW [249] / 69 kW - 21 MW [250] / 30 kW – 7,7 MW [251]

Table 3-8: Cooling capacity of the different cooling systems[254]

Maintainability and life expectancy

A further important factor to consider is the servicing and the expected lifespan of the system. Chiller based systems have most of their components located in a dedicated plant room which allows for the maintenance to occur without disrupting the functionality of the building, although being more sophisticated they require specially trained personnel. DX systems on the other hand, are usually installed adjacent to or inside the cooled room and have to be maintained in the same occupied premises. Compact DX systems have life expectancy of 10 to 15 years, while big chilled water systems are expected to function from 20 to 25 years.[255-256]

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[249] P. Riviere, ARMINES (2012), http://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Working_Documents/Task_1_Lot_6_Air_Conditioning_Final_report_July_2012.pdf - Date of access:14.3.2017

[250] Mitsubishi Electric UK, http://library.mitsubishielectric.co.uk/ - Date of access:14.3.2017

[251] Daikin General Catalogue 2017, http://www.klimamichaniki.gr/clientfiles/file/Daikin%20Software/General%20Catalogue%202017_Product%20Catalogue_ECPEN17-500_English.pdf – Date of access:14.3.2017

[252] Midea, http://cac.midea.com/mideacac/product/Chiller_System/2_pipe_fan_coil_units_23493/201506/t20150610_180794.shtml - Date of access:14.3.2017

[253] Airedale UK, http://www.airedale.com/web/Products/Chillers.htm - Date of access:14.3.2017

[254] Own table

[255] Cf. ASHRAE, http://www.culluminc.com/wp-content/uploads/2013/02/ASHRAE_Chart_HVAC_Life_Expectancy%201.pdf - Date of access:17.03.2017

[256] Cf. A. Bhatia (2012), p. (24)

Load profile

In many cases the expected load profile may have a decisive role when choosing an air conditioning system, e.g. in cases where a non-consistent load profile is present e.g. large parts of the building are unoccupied for extended periods, a chilled water system, which cannot be shut off completely would run at part load, thus resulting in poor performance and high energy consumption. On the contrary, local DX systems could be completely shut off when not needed, thus catering for potential energy savings.[257]

Load sharing

Load sharing is another important factor when choosing a new air conditioning system. If the system consists of multiple air conditioning units, this means that the loads cannot be shared on building-wide basis and the capacity of the single unit shall be designed for the case of peak load. A central system on the other hand allows load sharing and has also the ability to shift cooling power from one part of the building to another, thus reducing the potential size of the cooling unit.[258]

Economy of scale

Chiller-based air conditioning systems allow economies of scale, and normally the price per KW installed capacity reduces drastically for bigger chillers. DX systems on the other hand, cannot benefit from economies of scale, as they usually consist of many lower capacity units. [259]

Precision control

There are many applications which require precise temperature and humidity control like server rooms, data centers, laboratories, etc. Precision air conditioners, which are also referred as close control units (CCU) or computer room air conditioner (CRAC), are refrigerating equipment designed specifically to provide precise control over the temperature and humidity levels.[260] For this application both chiller-based systems as well as DX units are being used.

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[257] Cf. R. Miller, M. R. Miller (2006), p.(234)
[258] Cf. A. Bhatia (2012), p.(23)
[259] Cf. A. Bhatia (2012), p.(21)
[260] Cf. HIdROS, http://www.hidros.eu/applications/precision-air-conditioners - Date of access:18.03.2017

Building design – passive and active zone

The shape of the building and the passive to active zone ratio could have a decisive impact on the building energy performance regarding the lighting, ventilation and air conditioning systems and therefore the choice of air conditioning system. The passive area is the area that could be passively conditioned and normally it extends 6-8 m from the perimeter of the building depending on the height of the ceiling, while the active area in the building's interior and demands artificial lighting, ventilation and air conditioning.[261]

Figure 3-4: Deep plan (left) versus Shallow plan (right)[262]

Figure 3-4 shows the two most typical building designs – the deep plan and the shallow plan. Deep plan buildings are more compact and have a lower surface for heat loss, but because of the low passive to active zone ratio have the highest energy consumption as the depend strongly on artificial lighting and ventilation. Shallow plan buildings on the other hand, are designed with higher passive area in mind and have therefore significantly lower energy demand compared to other buildings.

Differentiation of the air-conditioning systems by their application

Complying with the selecting criteria stated in the previous section, it can be concluded that some cooling system types are more appropriate to use in certain application scenarios than others as it can also be seen from the following Table 3-9 below. The table coming from the Energy-Using Product Group Analysis (2012) and more specifically the Air-Conditioning systems summarizes and evaluates the performance of the different conventional cooling technologies in the different building applications. The best suited cooling technology for the respective applications is marked with XXX, the less suited with XX and the least appropriate with X.

[261] Cf. D. King, BSD (2009), p. (48)
[262] D. King, BSD (2009), p. (48)

		System type							
		Chiller-based systems					Air-Conditioners		
		All-air		Air-water					
Building type	**Sub-type**	Constant Volume (CV)	VAV	Fan coil & Induction	Chilled ceiling	Chilled beam	Single Split	VRF/ Multi split	Rooftop
Residential					X		XX	XXX	
Office	Shallow plan		XXX	XXX	XXX	XXX	XX	XXX	X
	Deep plan	X	XXX	XXX	XXX	XXX		XX	
Retail	Small shop						X	XXX	XX
	Large store / Supermarket	XXX		X					XX
Hotel	Public areas	XXX						X	XX
	Bedrooms		X	XX			X	X	
Theaters / Cinemas / Large spaces		XXX		X					XX

Table 3-9: System types and their application[263]

As evident from the table, the most suitable solutions for the residential sector are the direct expansion split systems, although chiller-based chilled ceiling systems are also appropriate. When both systems are compared, the split technology is more compact and has lower installation as well as maintenance costs as these are usually preassembled and therefore can be installed pretty quickly, which makes them more affordable and thus more desirable.

For commercial applications where bigger cooling capacities are demanded such as in offices, direct expansion VRF systems and different variations of chiller based systems are used. Depending on the office space distribution, all-air ducted systems are preferred in open type offices with a predominant uniform environment. In offices where the space is divided into multiple smaller subspaces, an air-to-water chiller-based system or a DX VRF system with individual terminal devices would be the better option as they both provide individual room temperature control. The retail sector so far is dominated by the all air CV chiller-based and the rooftop systems, both well suited for commercial applications. While the range of the chiller-based CV systems goes up to several MW and are therefore used to condition larger areas, rooftop systems are available also with smaller cooling capacities, appropriate for smaller applications. The advantage of the rooftop unit is that it is scalable, and by using a couple of these units, even bigger cooling demands could be met. Hotels typically use

[263] P. Riviere, ARMINES (2012), p. (51)

a combination of an all-air CV rooftop system for the larger open public areas and depending on number of bedrooms a smaller direct expansion split system or an air-to-water chiller-based system for bigger room numbers, both of which provide individual room temperature control. The last category comprises large open spaces such as theaters and cinemas. As in the retail sector, best suited for such applications are the CV chiller based and the rooftop systems. Both of them are capable of maintaining comfortable conditions in large spaces set for uniform and more or less constant air cooling requirements.[264]

The next Table 3-10 is an own illustration representing a further development of the original table, adopted from the 2012 Energy-Using Product Group Analysis. Now it considers the areas of application of the SOFC CCHP unit identified in section 3.3), which are marked with red X. The table also compares the system's applicability to the existing reference cooling technologies, thus making possible to identify the reference technologies that the SOFC CCHP system is competing against. The fields marked with a green X key out the main competitors of the SOFC CCHP unit in the respective building types.

		System type								
		Chiller-based systems						Air Conditioners		
		All-air		Air-water						
Building type	**Sub-type**	Constant Volume (CV)	VAV	Fan coil & Induction	Chilled ceiling	Chilled beam	SOFC CCHP	Single Split	VRF/ Multi split	Rooftop
Residential					X		X	XX	XXX	
Office	Shallow plan		XXX	XXX	XXX	XXX	XX	XX	XXX	X
	Deep plan	X	XXX	XXX	XXX	XXX	XX		XX	
Retail	Small shop						XX	X	XXX	
	Large store / Supermarket	XXX		X						XX
Hotel	Public areas	XXX							X	XX
	Bedrooms		X	XX			XX	X	X	
Theaters / Cinemas / Large spaces		XXX		X						XX

Table 3-10: Application of the SOFC CCHP unit compared to the conventional technologies[265]

The SOFC CCHP unit uses an absorption chiller to generate cooling power and can therefore be classified as a chiller-based central air-conditioning system. With its cooling capacity of 5 kW it is well suited for bigger residential applications, but it can

[264] Cf. A. Bhatia (2012), p. (5ff.)
[265] Own table based on P. Riviere, ARMINES (2012), p. (51)

be also scaled to suit light commercial applications as well. In a combination with a chilled ceiling system or multiple fan coil units it would be an appropriate option for multi-family apartment buildings as well as small offices, small hotels and retail stores. However being first and foremost an electric power generator, the SOFC CCHP unit would be particularly appealing in cases where a need or desire for independent electrical energy supply is present.

As the SOFC CCHP system not long ago has been defined as a central air-conditioning system, from the table it is also noticeable that the main technologies it competes against are the other central type systems and namely – the VRF, the chiller-based and the packaged split and or non-split systems.

3.4.3 European cooling market

One way to describe the situation on the European cooling market is by observing the market's saturation. The saturation of the market is a term used to describe a situation, when "there are no first time-sales to existing buildings"[266], or put in other words, the market would be saturated, when in every building in Europe there is at least one air-conditioner. If the European cooling market saturation is compared to the one in Asia or in the USA, the European market could be described as a still undeveloped field.[267] As it can be seen from Table 3-11, in 2005 the cooling market saturation in both the commercial and residential sectors in Europe was significantly lower with respective 27% and 5%. For example in Japan, in the residential sector in average there were 2.4 AC units installed per household and at least 85% of all household had 1 unit. Not much different was the situation in the USA.

% Saturation	USA	Japan	Europe
Commercial	80	100	27
Residential	65	85	5

Table 3-11: Estimation of the cooling market saturation in Europe, USA and Japan (2005)[268]

According to the same report (2005), many studies on the European cooling market predicted a development comparable to the levels in Japan and USA.[269] The next figure coming from the Energy Efficiency and Certification of Central Air Conditioners

[266] Cf. European Commission (2016), p (11)
[267] Cf. A. Tvärne, H. Frohm, A. Rubenhag (2014), p. (13)
[268] Own illustration based on A. Tvärne, H. Frohm, A. Rubenhag (2014), p. (14)
[269] Cf. A. Tvärne, H. Frohm, A. Rubenhag (2014), p. (17)

(EECCAC) report confirms this hypothesis and reveals a projection of the expected cumulated air-conditioned area in Europe till 2025. The curve in Figure 3-5, which marks the expansion of the total cumulated air-conditioned area in the EU, shows a significant and consistent growth over the observed period from 1990 to 2025, which is supposed to increase more than five times compared to the initial numbers. This growth is expected to affect both the residential and the service sectors, however in different scale.

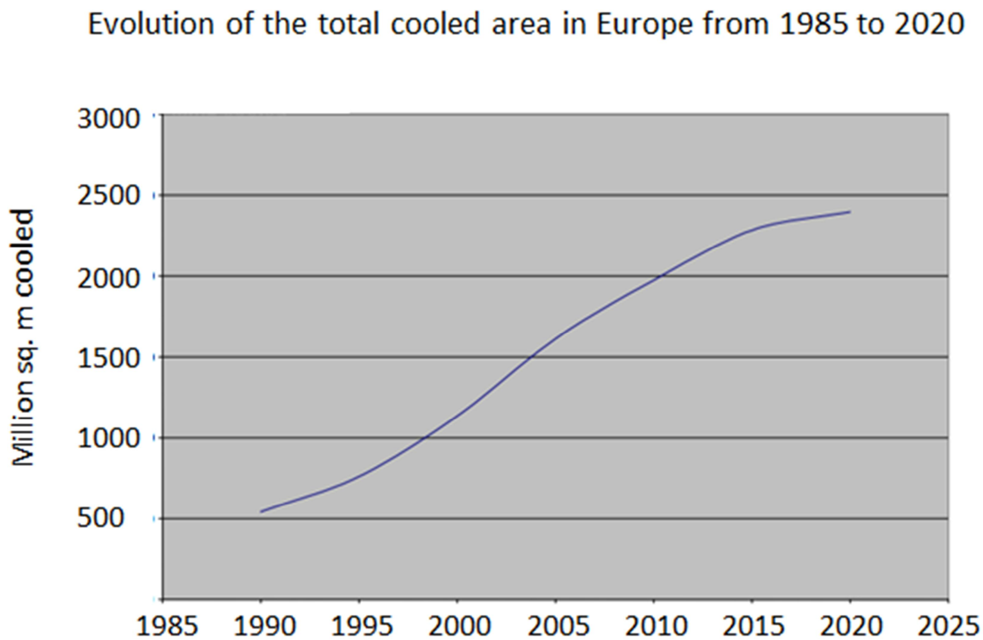

Figure 3-5: Projection of the total cooled floor area in Europe in million m^2 [270]

This positive trend was confirmed in the more recent "EU District Cooling Market and Trends" (2015) study by Tvärne et al. and the following Figure 3-6 shows that the projected increase rate from the study from 2003 has been sustained mostly because of the rapid development in the commercial sector.

[270] J. Adnot, Energy Efficiency and Certification of Central Air Conditioners (2003), p. (101)

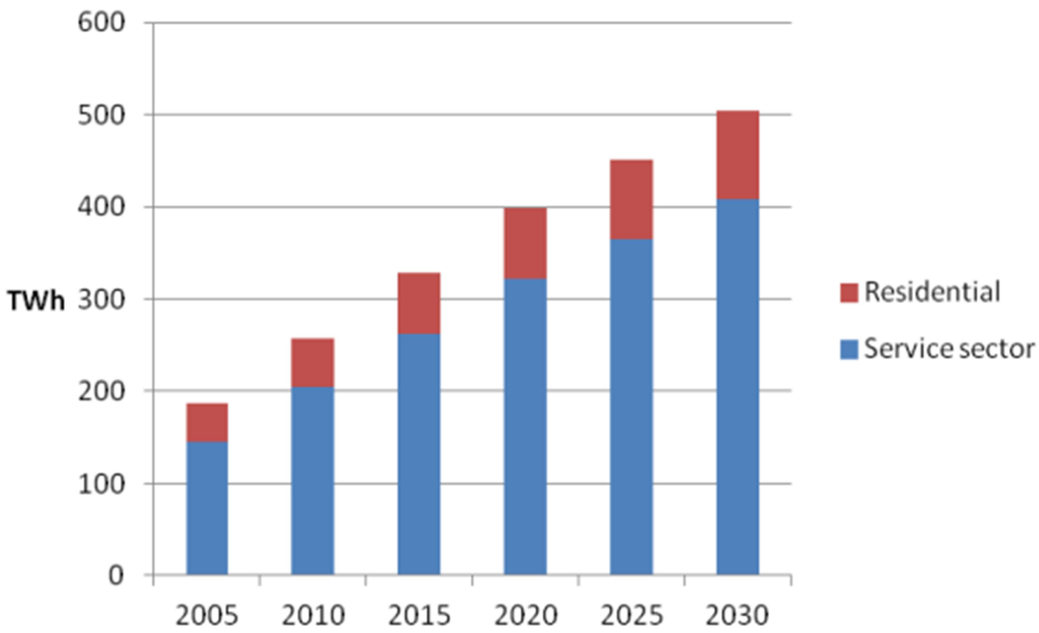

Figure 3-6: Cooling market estimation per year (2015)[271]

The cooling market expansion estimation from the “EU District Cooling Market and Trends” (2015) study corresponds to the following cooling saturation:

%	2010	2015	2020	2025	2030
Commercial	40	51	63	71	80
Residential	7	9	11	12	13

Table 3-12: European cooling market saturation (2015)[272]

When compared with the data from 2005, in 2015 the European cooling market saturation in the commercial sector has grown from 27% to 51% and in the residential sector respectively from 5% to 9%. By 2030 the saturation in the commercial sector is expected to reach the levels observed in the USA, while in the residential sector the levels are expected to remain significantly lower.

For the following detailed market analysis, in order to be able to distinguish between the residential and the commercial sectors, the 12 kW cooling capacity limit, set in the labeling directive 2002/31/EC and in the Directive on Energy Performance of Buildings

[271] A. Tvärne, H. Frohm, A. Rubenhag (2014), p. (19)
[272] Own illustration based on A. Tvärne, H. Frohm, A. Rubenhag (2014), p. (19)

2002/91/EC will be used. This limitation is set as a lower boundary to the central air condition systems and systems below 12 kW are counted as residential appliances, whereas the ones above are counted as commercial grade.

3.4.3.1 Analysis of the cooling market below 12 kW

The data used for this market analysis originates mainly from the following studies:

- ECODESIGN ENER Lot 10 study – "Preparatory study on the environmental performance of residential room conditioning appliances" from 2008
- European Commission Staff Working Document on the "EU Strategy for Heating and Cooling" from 2016.

The first study covers sales data from the following European countries: Germany, Greece, Poland, Spain, Portugal, France, Italy, UK, Czech Republic and Hungary, which according to information from the industry is believed to cover 85 to 90% of all sales within the EU.[273] According to the "EU Strategy for Heating and Cooling" study, in 2016 the EU market for cooling equipment <12 kW was only halfway towards saturation and the growth rate is expected to continue beyond 2030.[274] In total, the sales of the air conditioning equipment <12 kW was approximated at just over 3 million units per year in 2010 and are expected to reach 4.5 million units per year by 2030, which results in an annual growth rate of about 2%. [275]The climate, population and the economic structure are among the most significant factors that affect the air conditioning market, which assign the largest part of the air conditioning sales to Italy, followed by Spain and Greece, as shown in Figure 3-7. Italy and Spain alone account for more than half of all sales in the EU by installed capacity. The total air conditioning market value equals around 3 billion Euros per year and when the pricing differences between the single countries are considered, the distribution in the EU-27 on the whole resembles the sales percentages from Figure 3-10. [276]

[273] Cf. P. Riviere, ARMINES (2008), p.(8)
[274] Cf. European Commission (2016), p (3)
[275] Ibidem
[276] Cf. P. Riviere, ARMINES (2008), p.(8f.)

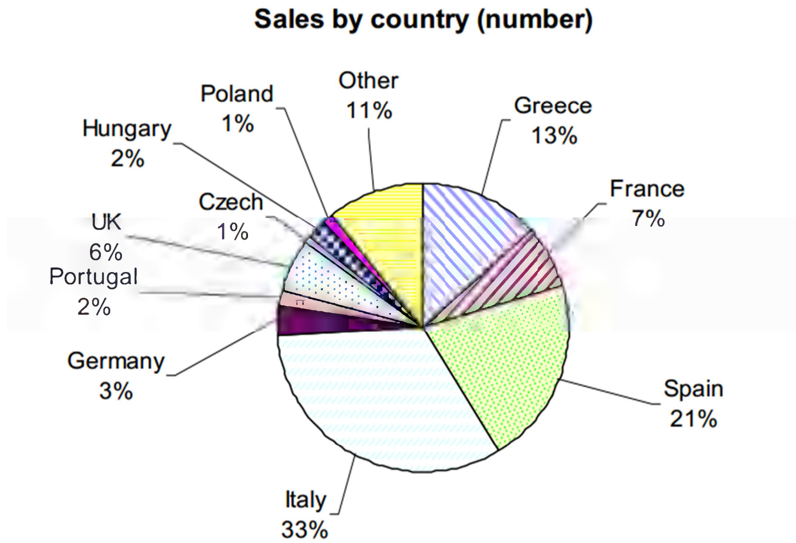

Figure 3-7: Air conditioning equipment sales by country, EU-27 all types <12 KW[277]

The next Figure 3-8 gives an insight on the sales of air conditioning systems based on the cooling technology of choice. As it can be seen from the diagram, the most desirable system type applied in the residential sector seems to be the non-ducted, single split air conditioning system.

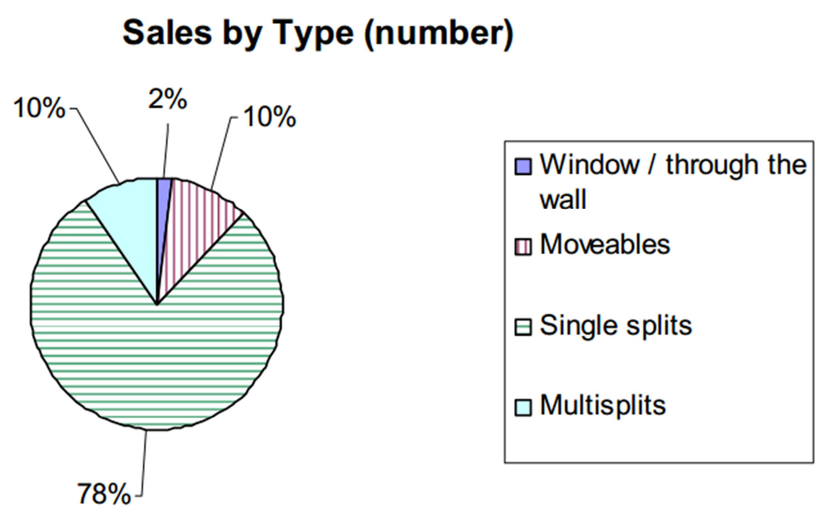

Figure 3-8: Air conditioning equipment sales by technology, EU-27 all type <12 kW[278]

[277] P. Riviere, ARMINES (2008), p. (8)
[278] Ibidem

With reference to the units sold, it can be concluded that the market segment <12 kW is dominated by the split system technology with single splits accounting for 78% of the total sales, followed by the multi splits with 10% and movables with also 10% of the market share. Summarizing, the split technology accounts for 88% of the total sales which equals around 2.340.000 single split, 300.000 multi split units and 300.000 movables in 2008.

Although the air conditioning sector <12 kW has been labeled as residential, from the next Figure 3-9 it gets obvious, that by installed capacity about two thirds of these systems are actually being installed in the non-residential sector.

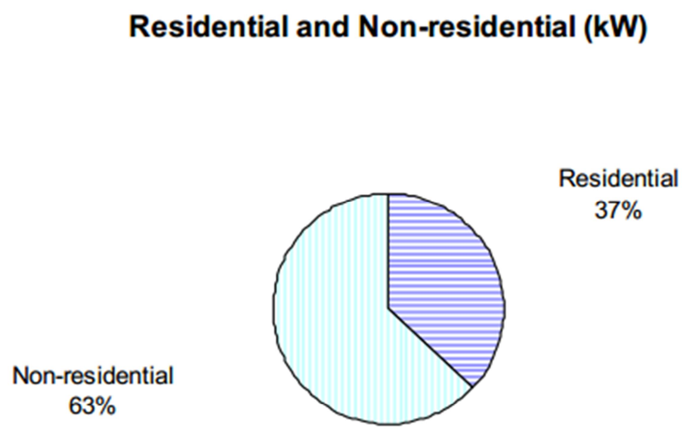

Figure 3-9: Air conditioners sales by sector, EU-27 all type <12 kW[279]

This residential to non-residential distribution however varies strongly according to the geographical location – while in central and northern Europe air conditioners are mostly installed in offices and light commercial building, in the Mediterranean area the installations in private homes are also from big importance.[280] This fact accounts for the high sales volume in the southern part of Europe.

The next Figure 3-19 gives one more piece of information about the type of systems installed in non-residential buildings. As it can be seen from the graph almost 95% of all systems are of the split type and if the information from Figure 3-17 is also considered it can be concluded that multi split systems are being installed mostly in non-residential buildings, while the use of movables is limited to the housing application.

[279] P. Riviere, ARMINES (2008), p. (12)
[280] Cf. P. Riviere, ARMINES (2008), p.(14)

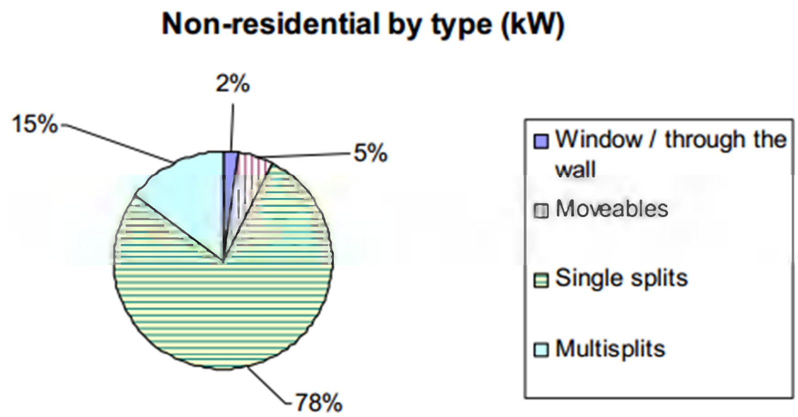

Figure 3-10: Non-residential air conditioning market distribution, EU-27 <12 kW[281]

This analysis provides interesting findings regarding the market segmentation of the cooling technologies sector <12 kW. This sector is clearly dominated by the split technology and even more interestingly, two thirds of the total cooling capacity goes to the non-residential buildings. Out of those units, almost 80% are of the single split and 15% of the multi split type. This practically means that all of the multi splits and around 50% of the single split units in the sector <12 kW are installed in non-residential buildings.

3.4.3.2 Analysis of the cooling market above 12 kW

The next part of the analysis covers the cooling systems with capacities >12 kW. This market segment is more diverse and there is more information available on the topic. For the completion of this analysis three main information sources were used:

- ECODESIGN ENTR Lot 6 study - "Sustainable Industrial Policy – Building on the Ecodesign Directive – Energy-Using Product Group Analysis/2 Lot 6: Air-conditioning systems" from 2012
- European Commission Staff Working Document on the "EU Strategy for Heating and Cooling" from 2016
- Market sales reports from Eurovent Market Intelligence (EMI).

As already mentioned this sector is much more diverse in terms of the available technologies – besides the split technology (single, multi and ducted splits), packaged air conditioners (rooftops), VRF systems and central plant chilled water systems

[281] P. Riviere, ARMINES (2008), p. (15)

(chillers) are available. The later mentioned technologies are of bigger capacities than the split systems and are usually applied as central air conditioning systems and therefore focused on slightly bigger applications with multiple premises needing to be cooled. The Figure 3-11 below gives information about the estimated market share of the different cooling systems by installed cooling capacity in 2008.

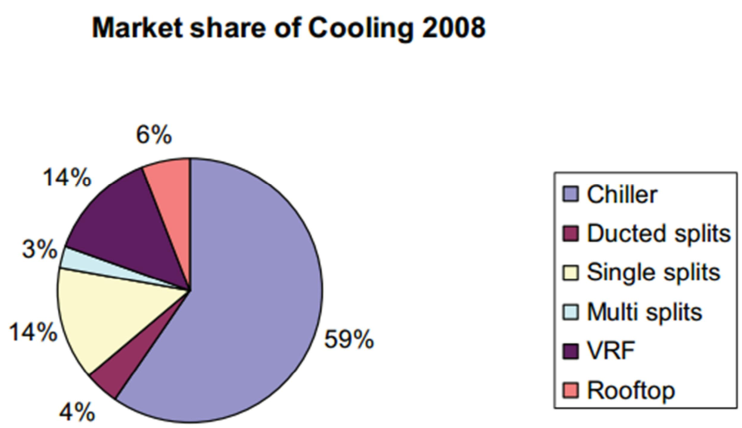

Figure 3-11: Market share of different air conditioning systems >12 kW by cooling capacity, EU-27[282]

As it can be seen from the diagram, chillers-based systems were by far the preferred technology with almost 60% of the market by installed cooling capacity. On second and third place were the Single splits and VRF systems both with 14% market share, followed by the Rooftops, Ducted splits and the Single splits respectively with 6%, 4% and 3%. However, as chiller-based systems operate also in large scale MW cooling applications this graph might not be so representative regarding the sales numbers. The next two Figures 3-12 and 3-13 though give more accurate approximation of the sales figures of the cooling systems >12kW. The first graph represents the development of the cumulated stock of central air conditioning products in the period 1990-2025, while the other one the estimated the sales numbers over the observed period. At this moment it is important to point out that the sales graph considers new installations in new and existing buildings as well as replacement installations of old equipment, whereas the graph estimating the stock considers only new installations which would therefore lead to an increase of the cumulated number of the installed cooling systems, e.g. the stock.

With regard to Figure 3-12, as the cooling market saturation is still at its low levels, most of the sales come from new installations in existing buildings, which supports the

[282] P. Riviere, Armines (2012), p. (7)

fact that the market is still away from reaching maturity. Once the market reaches its saturation point in the long run, all of the sales will become replacements or new installations in new buildings.[283]

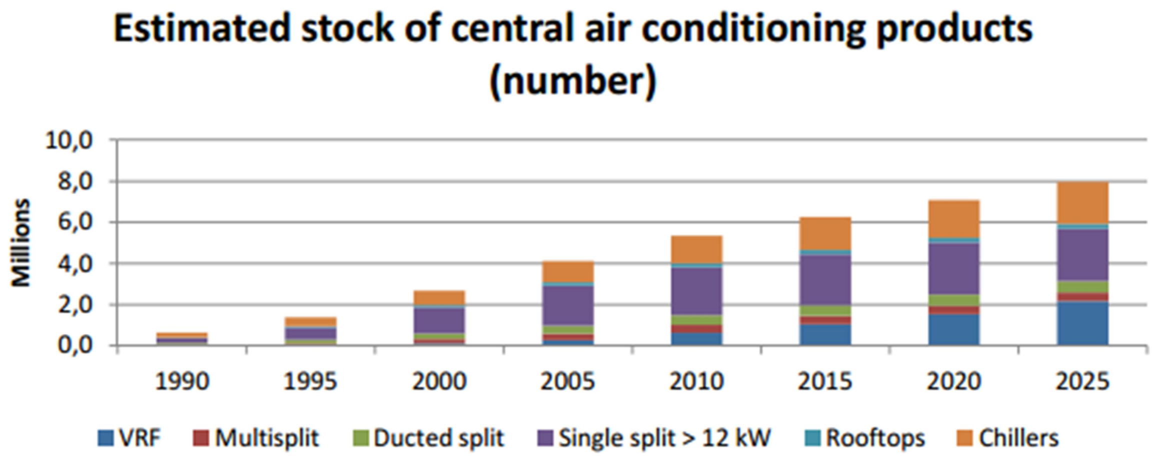

Figure 3-12: Estimated stock of central air conditioning products by cooling capacity[284]

From the above lying Figure 3-12, which describes the cumulated stock of the air conditioning systems, can be summarized that apart from the VRF technology and partly the chiller-based systems, no significant growth is expected in the stock of the other cooling systems. By the year 2025 both VRFs and Chillers are expected to reach 2 million installed units. Single splits which used to have the biggest stock seem to have reached saturation point and as of 2015 no further growth in their stock is observed. For this reason it can be assumed, that all further Single split installations are actually replacements. The same assumption counts for Ducted split systems. Since 2015, their stock seems to stop growing.[285]

The next figure below shows the most relevant data to this market study and in particular how did the sales of cooling systems >12kW evolved since 1990 and their future development till 2025. For this reason this table will be used for the estimation of the sales numbers of the relevant technologies.

[283] Cf. R. Hitchin, C. Pout, P. Riviere (2012), p. (6)
[284] P. Riviere, Armines (2012), p. (9)
[285] P. Riviere, Armines (2012), p. (17)

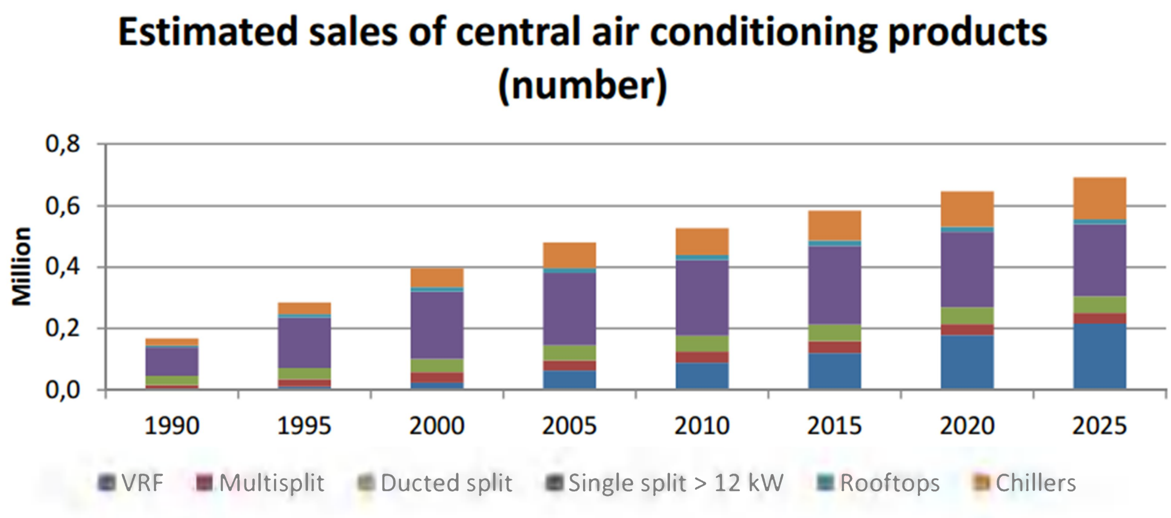

Figure 3-13: Estimated sales of central air conditioning products by numbers[286]

From the figure it could be concluded that in 2018 the Single split system would see the highest sales numbers with about 220.000 units sold occupying the lowest market segment below 20 kW, though as from the graph no further growth is to be expected. According to the same figure, in 2018 on second place in sold systems numbers will be the VRF cooling system with about 150.000 units per year. Moreover, it is the VRF system's sales who are really expected to progress within the observed time period with an annual growth rate of 8.6%[287]. By year 2025, the annual sales are to reach over 200.000 units, thus establishing themselves as the market leader in the middle market segment from 10-150 kW. The following Figure 3-14 gives a good overview over the distribution of the capacities of the VRF systems sold in the year 2012, with the red curve denoting the cumulated VRF system sales from that period. According to the figure, if the VRF system sales below 20 kW_{cool} are summed up, they would represent about 15 % of all sales from that time period. If this distribution would remain more or less stable, in 2018 this will result in about 22.500 units.

[286] P. Riviere, Armines (2012), p. (10)
[287] Cf. P. Riviere, Armines (2012), p. (20)

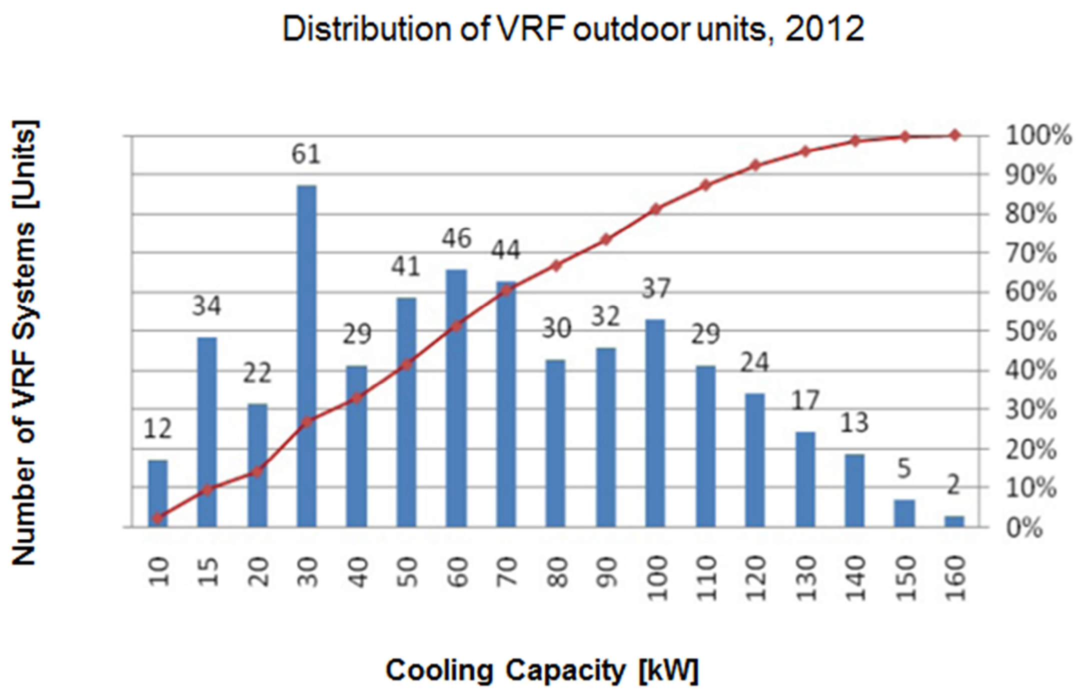

Figure 3-14 VRF capacity distribution of purchased units in 2012[288]

Another system type worth considering is the Ducted split system. Although their sales numbers seem to have stopped growing at some point after 2000, they remain appealing to customers with expected 50.000 units in 2018. With their cooling capacity range between 5 and 80 kW_{cool} and assumed 25% of those below 20 kW_{cool}, it results in 12.500 units per year around 2018.

The last significant player according to the graph is the Chiller-based system. Though these types of systems are available from 5 kW to 15 MW in size, their niche market are bigger central cooling applications, where they practically have no competitors. As from the graph, the Chiller-based systems are expected to reach about 100.000 units in 2018. The next Figure 3-15 gives a more detailed view on the Chillers-based system market in 2008. Out of all systems sold in 2008, two thirds had a cooling capacity smaller than 50 kW and 47% of the total referred also as “mini chillers” had cooling capacity of less than 17.5 kW.

[288] REHVA Journal, March 2014, p. (39)

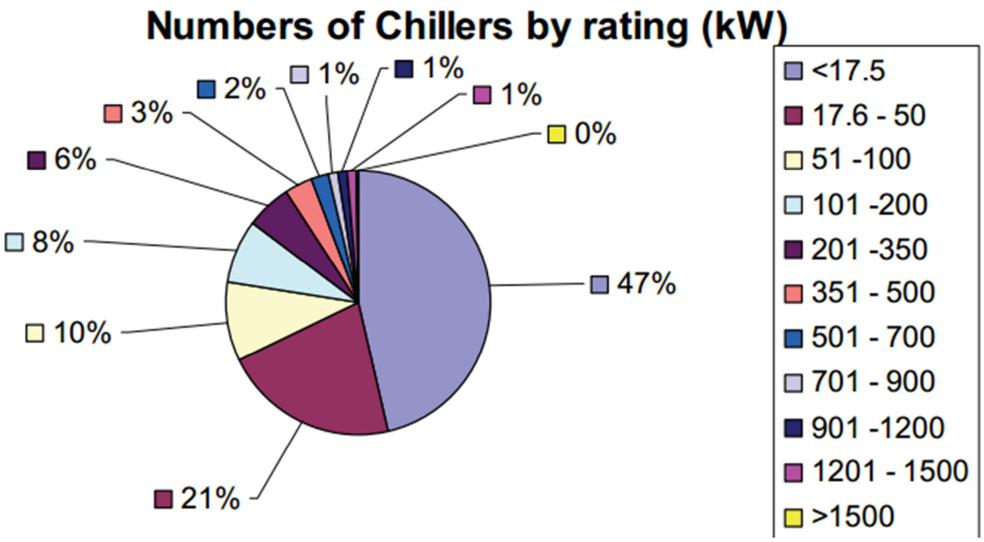

Figure 3-15: Segmentation of the 2008 chillers market by cooling capacity[289]

According to the Eurovent Market Intelligence (EMI) study from the same period, in 2008 there were about 75.000 systems units sold in Europe and out of those around 51.000 units had capacity of less than 50 kW.[290] If we take the information from both the EMI and ARMINES studies, it is possible to assume that the market share of chiller-based systems under 17.5 kW accounted for around 38.000 units in 2008. The next Figure 3-16 illustrates the market development of the chiller-based systems in Europe in the 2008-2015 periods. “Historically, there is an empirical relationship between the growth in the EU-27 GDP and the growth in the chiller sales”[291] and this could be seen in the drop in the sales in 2009/2010 caused by the global economic crisis from 2008-2009. As the European economies started to recover in the post crisis year, the chiller market followed as well.

[289] P. Riviere, Armines (2012), p. (26)

[290] REHVA, http://www.rehva.eu/fileadmin/hvac-dictio/05-2012/p45-48_emi.pdf - Date of access: 25.5.2017

[291] P. Riviere, Armines (2012), p.(13)

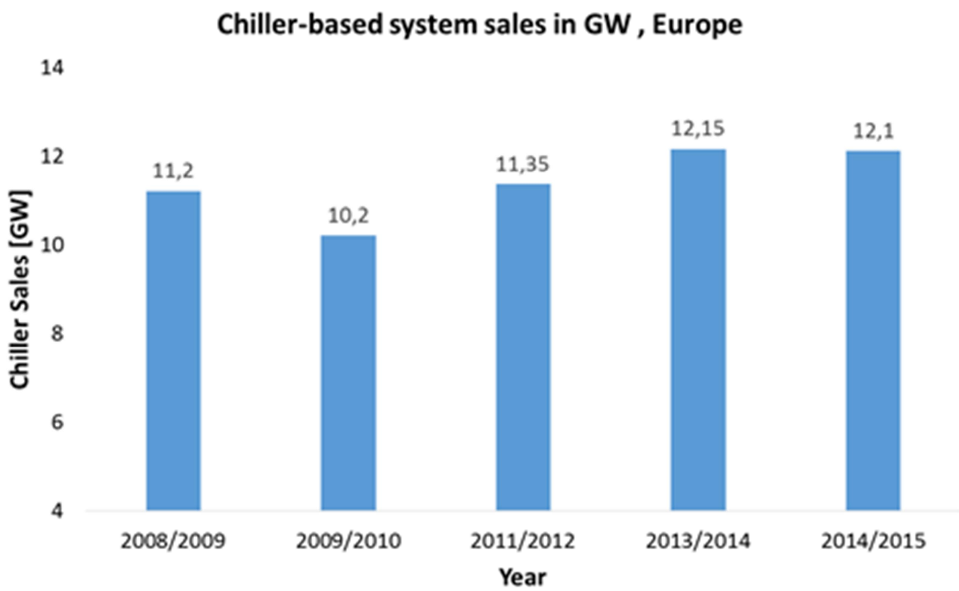

Figure 3-16: Chiller-based systems sales in Europe 2008-2015[292]

According to Figure 3-16 based on EMI sales reports, Chiller-based systems sales have recovered in the post crisis years and based on the estimated sales numbers from Figure 3-13, they would experience a slight but steady annual growth of about 6% and reaching 100.000 unit in 2018 and about 120.000 units by 2025. If the market distribution according to the system capacity from 2008 remains, about 50% of all systems or about 50.000 units will have a capacity below 17.5 kW.

3.5 SOFC CCHP system market potential

After analyzing the probable applications of the SOFC CCHP system in section 3.2) and their estimated number, it is possible to make an assessment of the system market capacity. The market capacity term represents the total absorbing capacity of a market for a particular product – the trigeneration system at a specific time moment, thus expressing the maximum theoretically possible sales number of the particular system.[293] Therefore as base for the calculation of the market capacity of the trigeneration system, the electrical power demand has been used. The following Table 3-13 summarizes the number of SOFC CCHP systems needed to match the electric power demand of all of the different application scenarios in Austria as well as in the EU-28 that have already been calculated individually for each application in section 3.2.1).

[292] Own representation based on Eurovent Market Intelligence (EMI) sales data (2008-2015)
[293] Cf. M. Schürmann (2011), p. (66)

	Austria		EU-28	
	Electricity Demand [GWh]	28 kW_{el} SOFC CCHP Modules [Amount]	Electricity Demand [GWh]	28 kW_{el} SOFC CCHP Modules [Amount]
Multi-family buildings	6899	28127	368598	1.502.764
Office buildings	5985	24402	266562	1.086.768
Hotels	1309	5336	27009	110114
Supermarkets	1018	4151	35266	143778
Data centers	840	3425	55	224234
Telcom base stations	1163	4743	47174	192329
Total [Amount]	**17214**	**70181**	**744664**	**3.259.985**

Table 3-13: Market capacity of the 28 kW_{el} SOFC CCHP Module in Austria and in the EU-28[294]

According to data from the table, based on the existing building stock and their electrical demand, the market capacity of the SOFC CCHP systems is estimated at **3.259.985** units. Put another way, this number represents the theoretically maximum number of SOFC CCHP modules that would be needed to satisfy the electric power demand in the identified application field. The above stated number however does not consider the purchase power of the population or the cooling demand of these applications.

As the market capacity number represents a theoretical approximation based solely on the electrical demand, the cooling technologies market represented by the competitor cooling systems was also investigated as they provide more realistic information based on the yearly sales reports and sales projections for the near future. The next Table 3-14 covers the findings from different market studies covered in section 3.3) and presents the estimated market sales data of cooling systems below 20 kW_{Cool} cooling capacity. The data covers both the sector below and above 12 kW_{Cool} cooling capacity. Although the ducted split and mini chiller systems capacity ranges below 12 kW_{Cool}, because of their central cooling operation type and therefore predominantly commercial application, they were covered in the study with the bigger cooling systems. As evident from the table, the total market for this type of cooling power generation products in 2018 is expected to reach **3.278.000** units. According to the table, the current market is dominated by the split system type. These systems along with the moveable air-conditioners, referred also as room air-conditioners in line with the cooling system classification from section 3.3.2), will rise to 96% of the total sales

[294] Own table

in 2018 or 3.170.000 units. On the other hand, central type systems such as the ducted split system, the VRF system or the mini-chiller system will be responsible for the remaining 4% of the total sales or **73.000** units, which also represent the actual market volume for central cooling systems below 20 kW_{Cool} cooling capacity. At this point if we consider how the reference system was defined in section 2.2) and namely as a central air-conditioning system consuming electric power from the grid, then the estimated number from above describes exactly the existing market volume of the reference trigeneration system. If the market volume of the reference trigeneration system is compared to the calculated market capacity, it equals mere 1,97% of the theoretically possible trigeneration system sales.

Cooling System	System Cooling Capacity [kW]	Estimated System Sales below 20 kW_{cool} in 2018, EU-28 [Amount]
Cooling Segment Below 12 kW_{cool}:		
Moveables	1,5 - 8	360.000
Single split system	2 - 12	2.800.000
Multi split system	5 - 12	360.000
Cooling Segment Above 12 kW_{coo}l:		
Single split system	12 - 15	220.000
Multi split system	12-15	30.000
Ducted split system	5 - 80	12.500
VRF system	10 - 150	22.500
Mini-Chiller system	6 - 17	38.000
Total		**3.843.000**

Table 3-14: Expected sales data for air-conditioning systems below 20 kW_{Cool} cooling capacity in 2018[295]

For the calculation of the market potential of the SOFC CCHP system, a 2,5% and 5% share of the calculated market capacity were assumed. The reason for these rather conservative values lies in the calculating approach of the market capacity but is also connected with the previously calculated market volume of the reference system and the newness and innovativeness of the technology. Moreover, because of the current prices of the SOFC CCHP technology, the market potential of the system is still highly dependent on governmental support schemes like the ENE-FARM program in Japan and the ene.field project in Europe.

[295] Own table

Using the estimated market capacity as a base and the calculated market volume of the reference trigeneration system as a reference value, the market potential of the SOFC CCHP system can be seen in the following table. The values vary from expected 81.499 to 162.999 units for respectively 2,5% and 5% share.

Market potential 28 kW_{el} SOFC CCHP	2,5% Share	5% Share
Modules [Amount]	81.499	162.999

Table 3-15: Market potential of the SOFC CCHP system[296]

Even if the estimated market capacity of the SOFC CCHP was overestimated by say 50% and represents **1.629.992** units, the new market potential of the SOFC CCHP system will look the following way:

Market potential 28 kW_{el} SOFC CCHP	2,5% Share	5% Share
Modules [Amount]	40.749	81.499

Table 3-16: Market potential of the SOFC CCHP system for the adjusted market capacity value[297]

Another interesting approach often cited in the literature in association with the adoption of a new technology is the "Diffusion of Innovations" theory by Everett Rogers. According to the author, the diffusion term is described as "the process by which an innovation is communicated through certain channels over time among the members of a social system"[298]. In line with his theory, Rogers states the social systems could be divided into five categories or five groups – the innovators, the early adopters, the early majority, the late majority and the laggards as can be seen from the following figure. Based on the innovativeness of each group, the adoption probability for a new technology can be estimated. Put in other words, if we assume that these five categories represent the market consumers as a whole, then their behavior would be decisive for the establishment of new product on the market. The Innovators represent without doubt the most venturesome group. This quality of theirs requires complex technical understanding in order to handle new technologies as well

[296] Own table
[297] Own table
[298] E. Rogers (1983), p. (5)

as the financial resources to cope with possible losses, due to unrewarding innovations.[299]

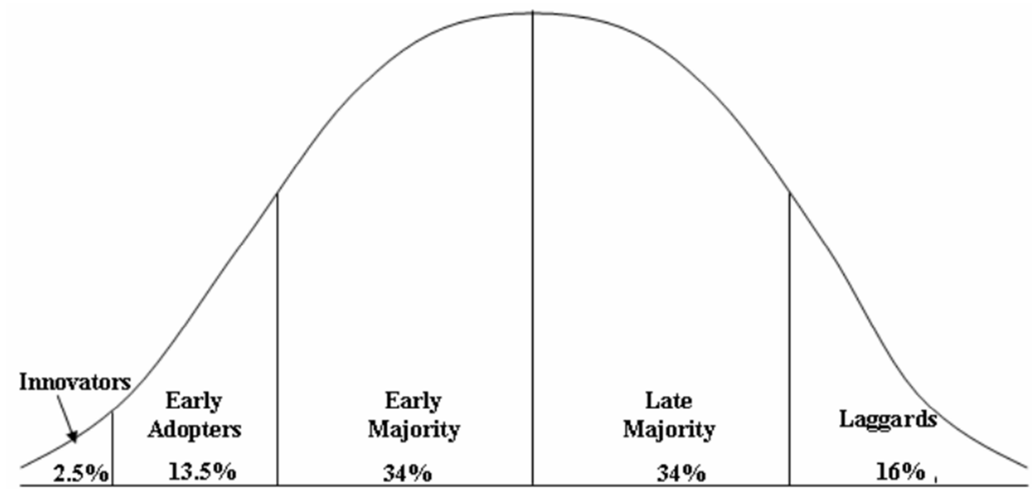

Figure 3-17: Adopter categories based on their innovativeness[300]

As the SOFC CCHP system represents a highly innovative and future oriented technology it is possible to assume that the innovators would represent the consumer group that would mostly be interested in the acquisition of this technology. With 2,5% share of the entire market, the innovators quota could be seen also as the market potential of the SOFC CCHP system in the initial phase of the technology commercialization. Calculated this way, the market potential of the SOFC CCHP system is not much different from the market potential value estimation from before, therefore it can be concluded that this value is representative for this type of innovative technology.

So far we have estimated the market capacity of the SOFC CCHP system at **3.259.985** units, based on the electric demand of the identified application field. Using this value as a base it was also possible to identify the expected maximum sales numbers for 2018 or the market potential of the system at **81.499** units. Based on the current market data it was further possible to identify the current sales volumes of the different reference trigeneration systems at **73.000** units in 2018. As previously stated, the market potential value gives an estimation of the maximum sales number of a product type at a certain period and is therefore not appropriate to be used in the approximation of the SOFC CCHP system costs. Therefore for the upcoming calculation of the system costs it was decided to go with a more conservative market

[299] Cf. E. Rogers (1983), p. (248)
[300] E. Rogers (1983), p. (247)

value approximation of the SOFC CCHP system of about **5.000** units per year, which on the one hand lays in the magnitude of the reference trigeneration systems sales but on the other hand also considers the much higher initial procurement costs compared to the reference systems.

4 System cost estimation

After determining the market potential of the SOFC CCHP system the following chapter introduces a model with the goal to estimate the cost needed to produce a single unit, depending on the purchased quantities per year.

4.1 SOFC system costs

The system costs of power plants are usually measured in EUR/kW installed capacity. The cost estimation of the SOFC module however will not be part of this thesis, as it has been already calculated at 2000 EUR per kW installed capacity for a production number of 5000 units per year. This value has been estimated as a target value by the AVL and would be further used for the estimation of the SOFC CCHP system costs.

4.2 Absorption chiller costs

In this section, the cost of the absorption chiller system is estimated in EUR per installed kW cooling capacity.

4.2.1 Current market situation

Absorption refrigeration machines as already stated in section 2.1.5) are thermally driven machines that need heat input in order to produce cooling power. With this in mind, until recently they were used primarily for utilization of waste heat in different industrial processes or in the production of power, thus limiting their production to large scale industrial class machines used mainly in district cooling projects. In the late years however, with the increased use of solar systems for energy and heat generation, a cheap source of heat has been introduced. This fact made solar cooling systems using small domestic class absorption chillers an attractive alternative to electric driven cooling machine. The system's potential awakened the interest across the cooling industry and many companies such as EAW, Invensor, Sortech, SolarNext (Germany), Pink (Austria), Thermax (India), Yazaki, Kawasaki, Mistubishi (Japan), Broad and Jangsu Huineng (China) have introduced small scale commercial absorption cooling systems fired by hot water.[301]

Although the information on the prices of absorption chillers is scarce and hard to find, some data was still available. According to the Canadian Office of Energy Efficiency of

[301] Cf. R. Kempener, IRENA (2015), p. (12)

Natural Resources in 2002 the cost of middle- to big scale absorption chillers from 300 – 15000 kW_{Cool} cooling capacity varied between 325 and 375 EUR per kW_{Cool} of capacity.[302] More recent information from 2017, which based on enquiry, showed that the prices of Yazaki absorption chillers vary between 1200 and 250 EUR per kW_{Cool} for hot water driven absorption cooling machine depending on their capacity with the Yazaki Company being one of the biggest absorption chiller produces worldwide and able to supply several thousand units per year. Research based information of the absorption machine market shows however that the price of absorption chillers operating on exhaust gases from the Chinese manufacturer Schuangliang[303] can drop down to 80 EUR per kW_{Cool} cooling capacity for a production number of 12000 units per year.[304] The market research showed however also, that there are no exhaust gas operating machines available in the commercial sector from 5-20 kW_{Cool} cooling capacity as these type of chillers are being used mainly for utilizing exhaust heat in industrial processes.

4.2.2 Absorption chiller cost model

For the realization of the current project and the testing of the SOFC CCHP unit a small capacity exhaust gas fired absorption chiller with 5 kW_{Cool} cooling capacity was needed. Due to the lack of devices in this cooling capacity segment, an external company was contracted to build a prototype. The price of this prototype was 31.000 EUR, or 6.000 EUR per kW_{Cool} cooling capacity. To estimate the price of this machine in case of a serial production with an approximated 5.000 units per year the learning curve model, described in detail in section 2.3.3) will be used.

The learning curve model that was first introduced in the 1930s is a widely used tool for cost forecasting and production planning. The model first described by T: P. Wright argues that each time the production number of a certain product doubles, the production costs decline by a certain amount. The reduction in the production costs is a constant known as the learning rate and it is typically given in percent. Learning rate of 80% means that every time the production doubles the production cost are reduced by 80%.[305]

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[302] Cf. NR Canada (2002), http://www.nrcan.gc.ca/energy/publications/efficiency/6037 - Date of access: 1.6.2017

[303] Cf. Schuangliang, http://sl-ecoenergy.com/1-4-flue-gas-fired-absorption-chiller/163319 - Date of access: 1.06.2017

[304] Cf. Alibaba, https://www.alibaba.com/product-detail/Flue-Gas-operated-LiBr-absorption-chiller_60278417439.html?spm=a2700.7724838.0.0.iHd8oU – Date of access: 1.6.2017

[305] Cf. M. Lieberman (1984), p. (2ff.)

As it can be seen from the following Figure, the learning curve slope varies for different products and industries, but for technical products the value lies between 72% such as for integrated circuits and 86% for automotive production. Therefore, for the calculation of the absorption chiller production curve an average value of 80% of the learning curve slope can be assumed.

Example	Improving Parameter	Cumulative Parameter	Learning-curve Slope (%)
1. Model-T Ford	Price	Units produced	86
2. Aircraft assembly	Direct labor hours per unit	Units produced	80
3. Equipment maintenance at GE	Average time to replace group of parts	Number of replacements	76
4. Steel production	Production worker labor-hours per unit produced	Units produced	79
5. Integrated circuits	Average price per unit	Units produced	72
6. Handheld calculator	Average factory selling price	Units produced	74
7. Disk memory drives	Average price per bit	Number of bits	76
8. Heart transplants	1-year death rates	Transplants completed	79

Table 4-1: Exemplary learning curve rates for different systems and technologies[306]

The production cost reduction of the n-th absorption chiller can be described by the following function:[307]

$$T_N = T_1 \times (N)^b \tag{24}$$

where $T_N =$ Costs for the Nth unit

$T_1 =$ Costs to produce the first unit

$$b = {}^{(\log \text{of the learning rate})}\!\big/_{(\log 2)}$$

$=$ Slope of the learning curve

For a learning curve with 80% learning rate, the slope is calculated as follows:[308]

[306] Own table based on J.Heizer, B. Render, C. Munson (2014), p. (778)

[307] Cf. J. Heizer, B. Render, C. Munson (2014), p. (778f.)

[308] Ibidem

$$b = \log(0{,}8)/\log(2) = -0{,}32196 \quad (25)$$

By using the slope value $\boldsymbol{b}$ and the known production cost of the first unit - the price of the prototype, the production costs of the absorption chiller were calculated for different production volumes per year. The resulting production curve of the absorption chiller can be seen from Figure 4-1.

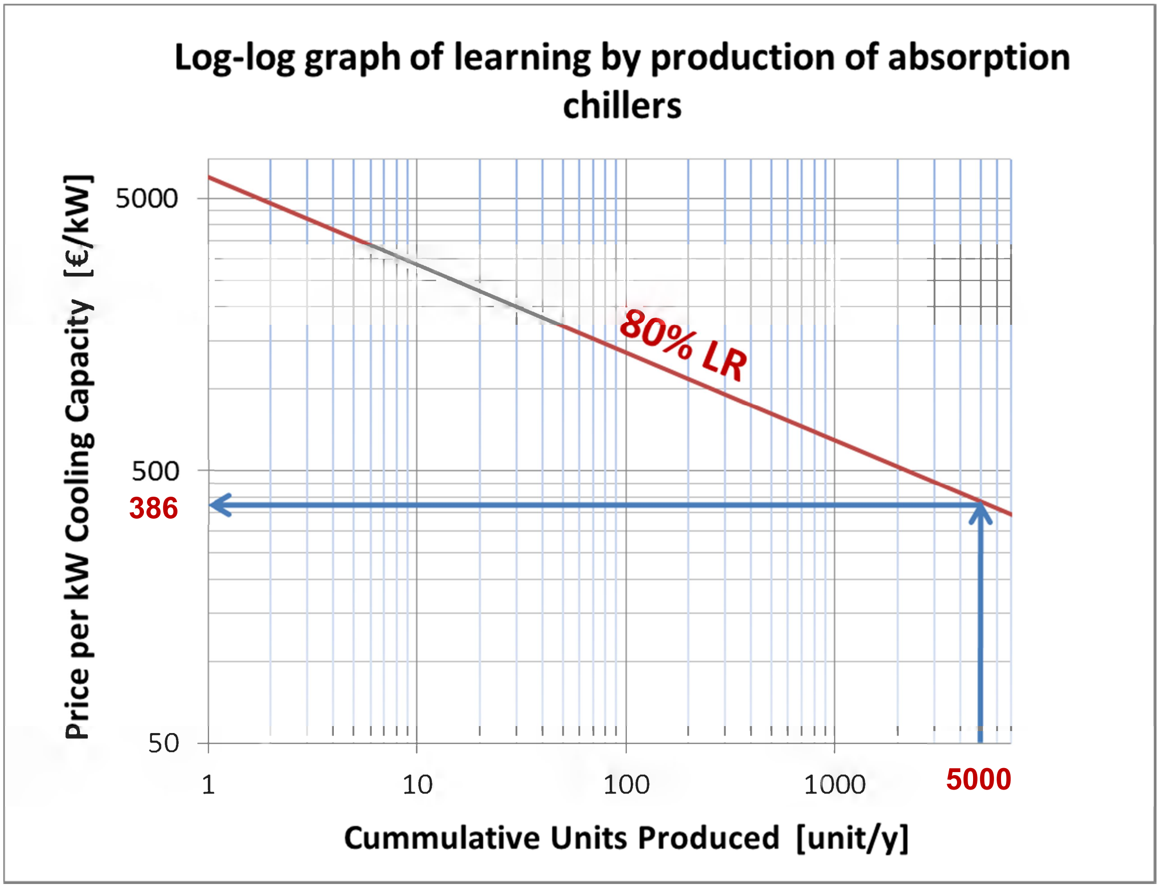

Figure 4-1: Absorption chillers production curve[309]

Over periods of time almost every organization learns and improves. By performing tasks over and over, firms and employees learn how to perform more efficiently and therefore both the time and costs needed to produce a product decline.[310] From the figure above it can be concluded that the production costs of the absorption chiller can be driven from 6000€ per kW_{Cool} for a single unit to 386 € per kW_{Cool} cooling capacity for a production volume of 5.000 units per year.

[309] Own illustration

[310] Cf. J. Heizer, B. Render, C. Munson (2014), p. (776)

4.3 SOFC CCHP system costs

The SOFC CCHP system costs represent the sum of the system costs of its two main components. As previously described in section 2.1) the combined system consist of a fuel cell with 28 kW_{el} electric capacity and an absorption chiller with 5 kW_{Cool} cooling capacity. The system costs of the two separate components are calculated by multiplying the specific system costs per kW installed capacity with the actual electric and cooling capacities:

$$Absorption\ chiller\ system\ costs = 5\ kW_{Cool} * 386 \frac{€}{kW} = 1.930\ € \tag{26}$$

$$SOFC\ system\ costs = 28\ kW_{el} * 2.000 \frac{€}{kW} = 56.000\ € \tag{27}$$

The overall SOFC CCHP system costs for a production volume of 5.000 units per year adds up to:

$$SOFC\ CCHP\ system\ costs = 28\ kW_{el} * 2.000 \frac{€}{kW} + 5\ kW_{Cool} * 386 \frac{€}{kW} = 57.930\ € \tag{28}$$

$$Total\ costs\ per\ kW_{el} = 57.930\ € \ /\ 28\ kW = 2.068\ \frac{€}{kW} \tag{29}$$

From the calculation above it can be seen that the system costs of the absorption chiller have a relatively minor impact on the overall system costs when compared to the fuel cell system costs.

5 Economic analysis of the SOFC CCHP system

In the following chapter answers regarding the economic viability of the SOFC CCHP system will be provided by the introduction of the TCO model. The excel based tool takes into consideration the complete amount of costs cumulated throughout the system's lifecycle and then compares them to the ones of the reference system. In a subsequent sensitivity analysis the different system parameters are investigated and the ones that are affecting the system the most will be highlighted.

5.1 Total Cost of Ownership

The Total Cost of Ownership model described in this section steps on the theoretical framework described in section 2.3.4) and represents an Excel-based calculation tool with the goal to encompass all possible costs that occur due to the acquisition and the usage of the SOFC CCHP trigeneration system over its lifecycle. As currently there are no trigeneration systems in serial production, the TCO tool compares the use of the SOFC CCHP to the reference system defined in section 2.2).

In order to be as extensive as possible, four different application scenarios in three geographical locations were considered - a single family house, an apartment block, an office building and a server room application. The different geographic locations – Seville (Spain), Vienna (Austria) and Milan (Italy) were chosen based on their different cooling/heating demands. By evaluating the procurement as well as the operational costs over the length of the usage period, the complete lifecycle cost of both types of systems can be estimated and a justified assessment of the SOFC CCHP economic viability is enabled. The following table summarizes the main characteristics of the systems as well as the most important assumptions made for the four different application scenarios in Vienna. The main system term characterizes the SOFC CCHP system with the possible complementary systems, while the reference system comprises the reference trigeneration system.

	Single Family House	Appartment Block	Office Building	Server room
Location	Vienna	Vienna	Vienna	Vienna
Conditioned area [m2]	140	2000	2000	54
Peak electric/cooling/heating demand [MW/y]	9,2 / 1,1 / 30	65,3 / 15 / 312,8	140,7 / 32,6 / 398,4	144,5 / 428,7 / -
Electric power price [ct]	22	22	22	22
Natural gas price [ct]	6,4	6,4	6,4	6,4
Feed in Tariff rate [ct]	8,6	8,6	8,6	8,6
Main System Configuration:	28 kWel SOFC CCHP	28 kWel SOFC CCHP + Multi-split AC System + Gas Furnace	28 kWel SOFC CCHP + VRF AC System + Gas Furnace	28 kWel SOFC CCHP + Packaged AC System
Main System Procurement Costs [€]	58500,0	64717,0	96127,0	68420,0
Main System Installattion Costs [€]	11700,0	12943,4	19225,4	13684,0
Main System Maintenance Costs [€/y]	585,0	647,2	961,3	684,2
Pel/Qcool	5,6	5,6	5,6	3,8
Electric efficiency [%]	60,0	60,0	60,0	60,0
Overall Efficiency [%]	99,0	99,0	99,0	76,0
Peak electric /cooling /heating capacity of the SOFC CCHP [kW]	28,0 / 5,0 / 16	28,0 / 5,0 / 16	28,0 / 5,0 / 16	28,0 / 5,0 / -
Electric /cooling /heating power produced by SOFC CCHP [MW/y]	245,8 / 43,8 / 140,16	245,8 / 43,8 / 140,17	245,8 / 43,8 / 140,18	245,8 / 43,8 / 140,19
EFLH el. power/ heating/	328 / 224 / 1872	2332 / 1440 / 4957	5025 / 1160 / 3255	5160 / 8670 / -
Electric /cooling /heating power utlization rate of SOFC CCHP [%]	3,7 / 2,5 / 21,4	32,0 / 48,0 / 37,6	49,0 / 44,0 / 13,1	100 / 100 / -
Amortization period SOFC CCHP system [y]	-	5,5 (feed in included)	6 (feed in included)	2 (feed in included)
Reference System Configuration:	Electric power from grid + Multi-split AC System	Electric power from grid + Mini VRF AC System + Gas Furnace	Electric power from grid + VRF AC System + Gas Furnace	Electric power from grid + Packaged AC System
Reference System Procurement Costs [€]	3544,00	33457,00	46145,00	10915,00
Reference System Installation Costs [€]	1772,00	16728,50	23072,50	5457,50
Reference System Maintenance Costs [€/y]	354,40	3345,70	4614,50	1091,50
EER AC	3,95	3,60	3,60	3,60
Gas Furnace AFUE	0,98	0,98	0,98	0,98
Peak electric/cooling/heating capacity [kW]	8,6 / 9,6	13,6 / 87,2	44,8 / 255,8	55,60
Electric/cooling/heating power produced [MW/y]	9,2 / 1,1 / 30	65,3 / 15 / 312,8	140,7 / 32,6 / 398,4	144,5 / 428,7 / -
EFLH el. power/ heating/ cooling [h]	on demand	on demand	on demand	on demand

Table 5-1: Characteristics of the systems investigated in the TCO tool[311]

[311] Own table

As evident from the table, the exact electric, heating and cooling power capacities of the technologies comprised in the reference system are not fixed but rather chosen depending on the energy demand of the application. On the other hand the capacities of the SOFC CCHP systems are set and therefore in cases where the system alone cannot match the cooling or heating energy demands of the different building types, complementary systems are implemented. As it can be also seen from the table, depending on the application scenario different utilization rates of the produced electric, heating and cooling power can be achieved that are further leading to different amortization periods. From the table it gets also evident, that there are two different modifications of the SOFC CCHP system. The difference between them being that in the server room application scenario no heating power is produced.

The structure of this section is oriented towards the design of the TCO Tool that can be seen in Figure 5-1. The tool is built in four consecutive stages – the Preparation phase, the TCO Configuration phase, the Operation Phase and the TCO Results, where the results are presented graphically.[312]

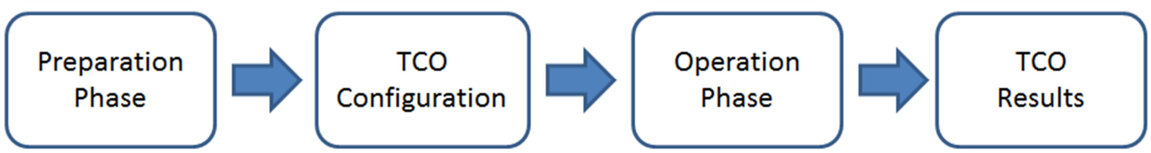

Figure 5-1: Structure of the TCO Tool

5.1.1 Preparation phase

The preparation phase itself comprises the following four steps – Cooling & Heating Loads, Installed Equipment, Equipment Specifications & Prices and Electric Load Profile.

5.1.1.1 Cooling and Heating Loads

The earliest stage of the TCO model summarizes the data from two studies – the ENTRANZE Project (2014) and the ACEEE Summer Study on Energy Efficiency in

[312] Cf. Bode et al. (2011), p. (9)

Buildings (2014). The first study, co-funded by the Intelligent Energy Europe Programme of the European Union models the "Heating and cooling energy demand and loads for building types in different countries of the EU"[313]. This report outlines the energy needs regarding heating, hot water and cooling for a number of building types, but also provides the base building characteristics concerning the electricity consumption and the building geometry. The data from the report is used to model the energy consumption the single family house, the apartment block and the office building. The next figure is an example from the report, describing the heating hot water and cooling demand of an apartment block building in Vienna, Austria.

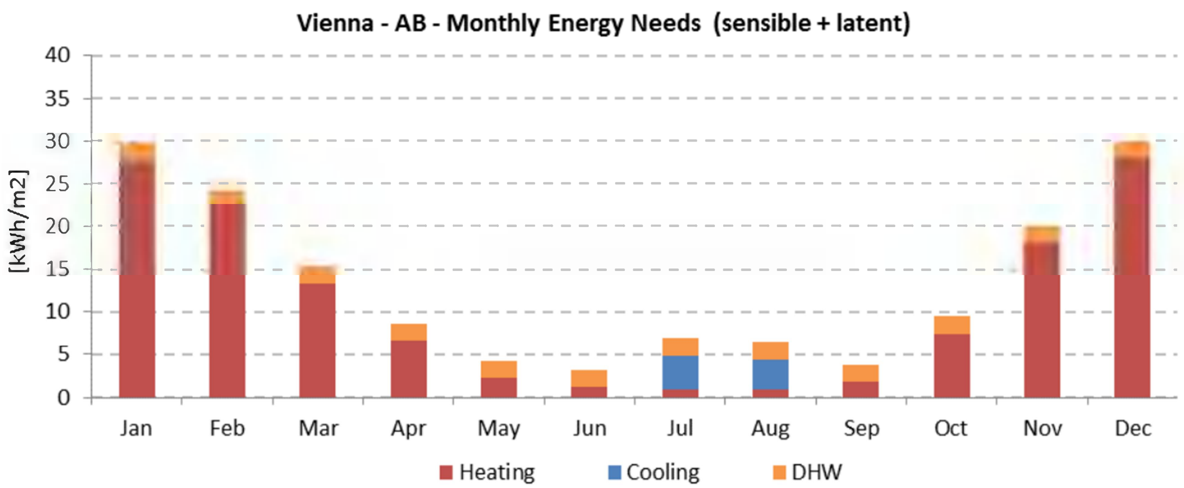

Figure 5-2: Monthly energy needs of an apartment block in Vienna, Austria[314]

The monthly cooling and heating loads for each building are calculated by multiplying the values taken from the above lying figure that are given in kWh/m^2 with the surface area of the building in m^2. For example in a building of 2000m^2 the heating load in December can be estimated at:

$$Heating\ [kWh/month] = 30\ [kWh/month * m^2] * 2.000\ [m^2] = 60.000[kWh/month\ ]$$

For the calculation of the peak heating load in December it was assumed that the air conditioning system was operated without stops in the heating season. Thus the peak heating load is calculated to:

$$Peak\ Heating\ Load\ [kW] = 60.000\ [kWh/month] \div 720\ [h/month] = 83{,}3\ [kW]$$

313 ENTRANZE (2014), p. (1)
314 ENTRANZE (2014), p. (42)

The same way, month for month were calculated the heating and cooling demands as well as the heating and cooling peak loads for the single family house and the office building for the three different locations.

The second study by the American Council for an Energy-Efficient Economy from 2014 focuses on the energy efficiency of small server rooms. For this reason the energy consumption of 30 small server rooms in 8 different locations was surveyed and out of those 4 server rooms were selected for detailed assessment. The following table gives an overlook of the energy demands of the particular server room that was used as a sample in the TCO model. The server room is located in California (USA), although as most of the small server rooms are situated on the inside of buildings the geographical location is of less importance. As it can be seen from the table, most of the energy is consumed by the IT Equipment, tightly followed by the cooling system, with minor parts going to the UPS and the Lighting system.

Power (Units in kW, except for PUE)	City of Walnut Creek
IT	15.1 [1]
Cooling	14.9 [1]
Lighting	0.1 [2]
UPS	1.3 [1]
Total load	31.4

[1] Directly measured. [2] Assumed or estimated.

Figure 5-3: Energy consumption of a server room in Walnut Creek (California)[315]

However at this point it must be stated, that the values from the table represent the measured electric power consumption. This means that the actual cooling power demand in the server room is much higher, as packaged rooftop systems as the one used in that server room have an EER of 3,3. This means that the actual cooling power demand equals:

[315] ACEEE Summer Study on Energy Efficiency in Buildings - Energy Efficiency in Small Server Rooms: Field Surveys and Findings (2014), p. (7)

$$EER = \frac{Q_{Cool}}{P_{el}} \tag{30}$$

$$Q_{Cool} = P_{el} * EER = 14{,}9\ [kW] * 3{,}33 = 49{,}6\ [kW] \tag{31}$$

One of the main characteristics of server rooms and data centers is their uninterruptable operation, thus it can be assumed that the values from Table 5-2 will remain constant throughout the year and represent the peak cooling and electric load.

5.1.1.2 Installed Equipment

After determining the peak cooling and heating values in the previous section, the next step is to choose appropriate equipment that can cope with the buildings energy demands. The next Table 5-3 shows a comparison of the equipment that was chosen for an apartment block in Seville (Spain).

Installed Equipment	Reference System	Main System
Cooling :	Daikin VRV System: 2 x REYQ8T	20 kW SOFC CCHP + Daikin VRV System: REYQ8T
Heating :		
Peak cooling load [kW]:	**40,28**	
Cooling Capacity [kW]:	44,8	42,4
Peak heating load [kW]:	**25,00**	
Heating Capacity [kW]:	44,8	86,4

Table 5-2: Installed Equipment in an apartment block in Seville (Spain)

For each application scenario, the air-conditioning system is dimensioned to match the peak cooling demand of the building, thus ensuring that even in the peak conditions the system will be able to cope. Because the specifics of the main system regarding the electrical to cooling capacity ratio a DX Multi split systems was chosen to complement the SOFC CCHP unit and in this way match the cooling demand. In this case the cooling capacity represents the sum of the SOFC CCHP system cooling capacity and the complementing DX Multi split system cooling capacity.

The following Table 5-4 displays the equipment that was chosen for an apartment block in Vienna (Austria). In this case where due the geographic location and the respective climatic conditions, the installed capacity of the air-conditioning system satisfies the cooling demand but is not sufficient to match the heating demand, complementing gas heating systems are selected. Because of their much lower exploitation and maintenance costs compared to reversible air conditioning systems, gas heating systems are much less expensive and therefore preferred to reversible air conditioning systems.

Installed Equipment	Reference System	Main System
Cooling : Heating :	Daikin Multisplit: 2 x 4MXS68 + 2 x Viessmann 300-W Gastherme 35	20 kW SOFC CCHP + Viessmann 300-W Gastherme 26
Peak cooling load [kW]:	**11,11**	
Cooling Capacity [kW]:	13,6	20,0
Peak heating load [kW]:	**83,33**	
Heating Capacity [kW]:	87,2	90,0

Table 5-3: Installed Equipment in an apartment block in Vienna (Austria)

As it can be seen from the table, the choice of air-conditioning system that would serve as the reference system is much more flexible, because of the much wider selection of system with different capacities. The heating capacity again represents the sum of the different implemented systems. The specifications of the individual systems stem from the producer catalogues and can be seen in the Annex of the thesis.

5.1.1.3 Equipment Specifications and Costs

This section summarizes the technical specifications as well as the procurement costs of the different cooling, heating and power generating products that have been referenced in the TCO model so far. Further in this section, important assumptions have been made regarding the installation and maintenance costs. The installation costs are one-time costs that need to be paid prior to or after the installation of the purchased system. For the SOFC CCHP system these has been approximated at 20% of the procurement costs, while for the other products respectively at 50%. The maintenance costs on the other hand are calculated on yearly basis and are due to maintaining procedures like general cleaning, lubricating moving parts, filter change, coolant refilling and occasional drive belt change in case of an air-conditioning system. For the SOFC CCHP the maintenance cost have been approximated with 1% of the procurement costs, because of the much higher procurement costs compared to the reference system but also because of the fact that both units – the fuel cell and the absorption chiller, have almost no moving parts and therefore not much to maintain. Furthermore the absorption chiller operates with harmful ammonia solution, thus minor leakage will not cause drop in the system pressure and pose risk to the operation of the system. Following this logic, the highest maintenance costs have air-conditioning systems as they work with gaseous coolant, whose level must be controlled on yearly bases and a compressor that also needs to be maintained. Their maintenance costs have been assumed with 10% of the procurement costs.

5.1.1.4 Electric Load Profile

The sections so far have covered the cooling and heating demands as well as the installed equipment for their generation. The focus of this section lies on the electric power consumption and generation. As already mentioned on several occasions, the SOFC CCHP unit is first and foremost an electric generator and for an economically viable application relatively constant electric power consumption is demanded. Further in this section we will investigate how much of the power generated by the fuel cell is actually utilized, how much is fed and how much is consumed from the grid.

First to begin with is the design of the electric power consumption. The Entranze study (2014) provides again with useful information regarding the consumption in the different building types that can be further split into consumption by electrical appliances and by the lighting system. For apartment block or in the residential sector in general these values come respectively to 4 W/m^2 and 3,5 W/m^2 as can be seen from the following Table 5-5. The table contributes also information on the main building geometries.

		ES, IT, FR	RO, AT,CZ, DE, FI
Building geometry	Num. of heated floor	4	
	S/V ratio	0,33m2/m3	
	Orientation	S/N	
	Net dimensions of heated zones	24,6 x 11,2 x 12,8m	
	Net floor area of heated zones	990 m2	
	Area of S. façade	315 m2	
	Area of E. façade	143 m2	
	Area of N. façade	315 m2	
	Area of W. façade	143 m2	
	Area of roof	54 m2	
	Area of basement	54 m2	
	Window area on S. façade	15%	30%
	Window area on E. façade	0%	0%
	Window area on N. façade	15%	30%
	Window area on W. façade	0%	0%
Internal gains	People design level	25 m2/people	
	Lighting design level	3.5 W/m2	
	Appliances design level	4 W/m2	

Table 5-4: Apartment building characteristics[316]

Thus by multiplying the appliances and lighting design values with the surface area of the building it is possible to calculate the theoretically maximum power consumption of the building, without considering the consumption of the air-conditioning system. For example for an apartment block building of 2000 m^2 the electric power loads due to the lightning and appliances can be estimated at:

$$Electric\ base\ load\ [kW] = (3{,}5 + 4)\ [W/m^2] * 2.000\ [m^2] * 10^{-3} = 15\ kW$$

The following Figure 5-3 was adopted from the US Department of Energy Commercial Reference Building database and it provides a more realistic perspective on electric power consumption in apartment buildings. The figure shows to what extent the installed electric power consuming devices are being used depending on the time of day. From the figure it can be seen, that the lights are usually operated in the early morning hours and reaching peak levels around 21 o'clock. The usage of Electric appliances on the other hand seems more evenly distributed, although distinct peak levels are measured around 17 o'clock.

[316] Own illustration based on ENTRANZE (2014), p. (17)

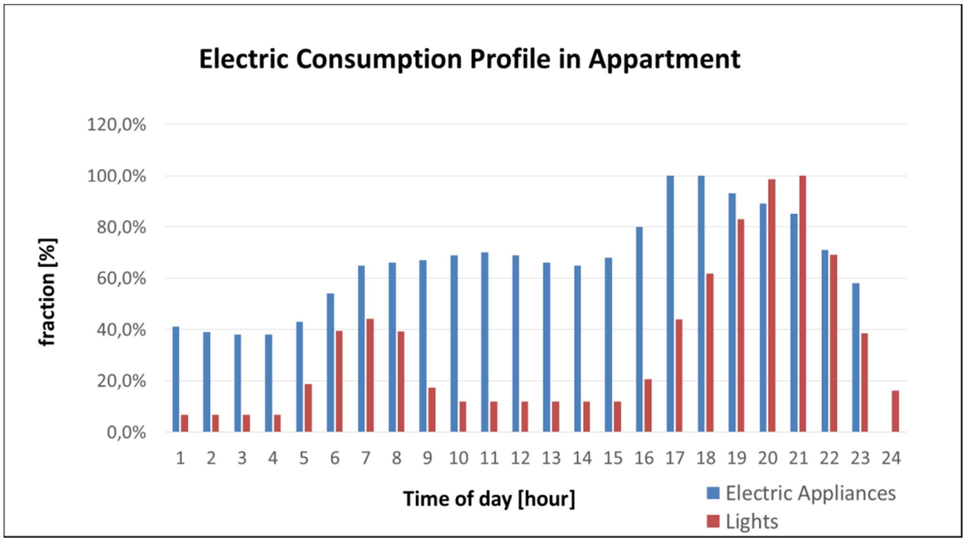

Figure 5-4: Electric power consumption profile in an apartment building[317]

When both of these profiles – the one representing the electric appliances and the other one the lighting system are multiplied with the respective design levels and afterwards summed up, it is possible to calculate the electric power consumed throughout the day. The cumulated electric power consumption of a 2000 m^2 apartment block can be seen in the next Figure 5-4.

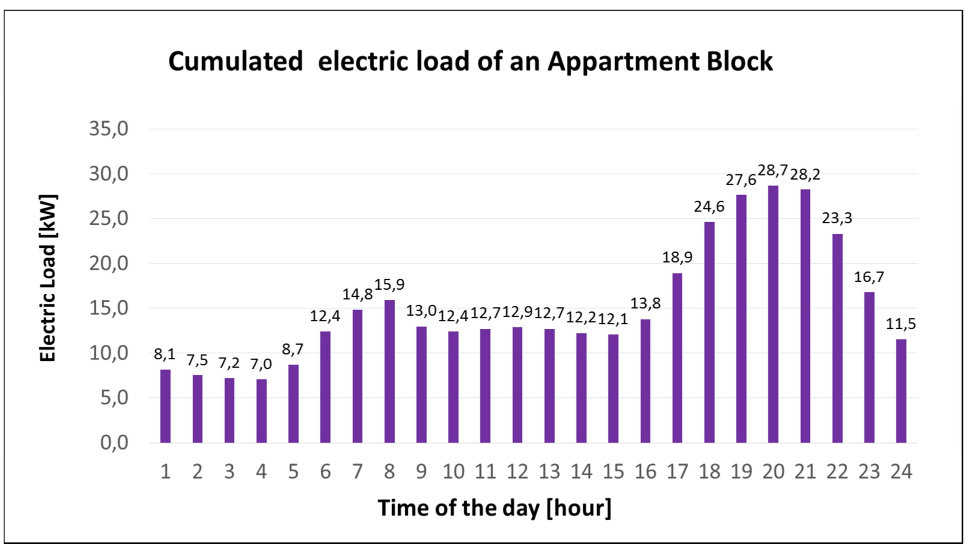

Figure 5-5: Base electric load of an apartment block[318]

[317] Own illustration based on US Department of Energy (DOE) Commercial reference buildings data

The electric consumption profile from the figure above shows the daily consumption of an apartment blocks resulting from the use of electric equipment and lights and can therefore be described as the base load. It can be also assumed that this profile will remain relatively constant throughout the year and that it is independent from the geographic location. The variable portion of the electric consumption of an apartment block is the one connected with the use of the air-conditioning system for cooling and heating purposes.

The electric load generated by the air-conditioning system can be established using the monthly cooling/heating loads from section 5.1.1.1) and the Energy Efficiency Ratio (EER) of the system in use.

$$EER = \frac{Q_{Cool}}{P_{el}} \quad (32)$$

$$P_{el} = \frac{Q_{Cool}}{EER} \quad (33)$$

By adding the respective monthly electric power consumption values coming from the air conditioning system to the base load it is possible to calculate the total electric power consumption month for month as shown in the Figure 5-5 below. The figure provides information about the consumption of electric power of an apartment block in July that is situated in Vienna.

[318] Own illustration

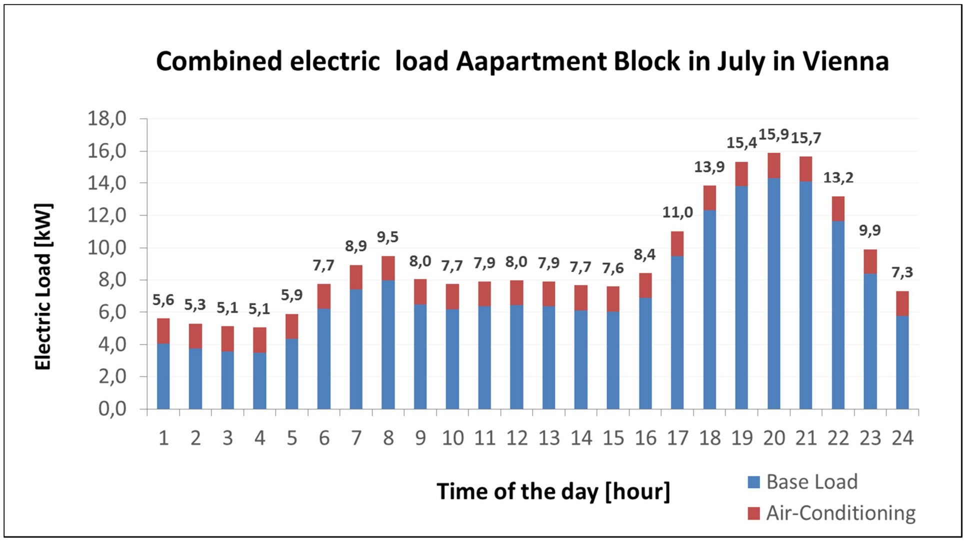

Figure 5-6: Combined electric power consumption in an apartment block in Vienna in July[319]

After estimating the combined electric power consumption profile it is possible to tell if the consumed energy came from the fuel cell or some of the energy was supplied by the electric grid. This would be the case if the peak load would exceed the fuel cell capacity of 28 kW_{el}. By carrying out this calculation for every month of every application we obtain the complete electric profile over the year for each application. These profiles provide information about the total power consumption as well as its origin. The next table provides information about the amount of energy produced by the fuel cell that has actually been utilized by the different applications.

28 kW_{el} SOFC CCHP unit			
Application Scenario:	Seville	Vienna	Milan
Single Family House	4%	4%	4%
Apartment Block	35%	32%	37%
Office Building	49%	49%	50%
Server room	100%		

Table 5-5: Utilization rate of the electric power produced by a 28 kW_{el} SOFC CCHP unit in the respective application scenarios[320]

As anticipated before, the highest utilization rate is provided in the server room scenario, due to their uninterruptable operation. In this way they manage to utilize almost the complete amount of the energy produced by the fuel cell. On second place

[319] Own illustration
[320] Own table

is the office building scenario with about a third of the produced amount. Third place goes to the apartment block scenario with about 16% followed by the Single Family House with mere 4% utilization rate. The low percentage of some of the applications makes them dependable on the feed in tariffs in the different countries.

5.1.1.5 TCO Configuration

The TCO Configuration phase is divided into two parts – the one covering the technical and the other the economic aspects of the respective application scenario. In the technical part the end goal is to estimate the consumption of resources on yearly basis due to the operation of the system. To do so, first the equivalent full load hours (EFLH) per year are calculated, although separately for each system, as some system may run on electricity while others on natural gas (NG). For example the EFLH for the main cooling system (28 kW_{el} SOFC CCHP) of a 2000 m^2 apartment block in Vienna are calculated as follows:

$$EFLH_{SOFC\ CCHP\_cool}\ [h/y] = \frac{Cool.demand\ [kWh/y]}{Cool.capacity\ [kW]} = \frac{7.200}{5} = 1.440\ h/y \qquad (34)$$

As part of the SOFC CCHP system for the generation of the cooling power, no electric power is consumed. On the other hand, in the same scenario a complementary cooling system is installed, whose EFLH are calculated the same way:

$$EFLH_{AC\_cool}\ [h/y] = \frac{Cool.demand\ [kWh/y]}{Cool.capacity\ [kW]} = \frac{7.800}{6{,}8} = 1.147{,}1\ h/y \qquad (35)$$

The same way are calculated the EFLH of heating and cooling for all systems and application scenarios. With the air-conditioning system EFLH the consumed electric power can be calculated. For example the consumed electric power by the complementing air-conditioning system in a 2000 m^2 apartment block in Vienna are calculated as follows

$$Electric\ power\ consumption_{AC}\ (MWh/y) = \qquad (36)$$

$$= \left(EFLH_{AC_{cool}} * Cool.capacity + EFLH_{AC_{heat}} * Heat.capacity\right) * \frac{10^{-3}}{EER_{AC}} =$$

$$= (1.147,1\,[h/y] * 6,8\,[kW] + 5.040\,[h/y] * 8,6\,[kW]) * \frac{10^{-3}}{3,95} = 12,9\,[MWh/y]$$

Further this section provides with information about the share of the used electric power that comes from the fuel cell and the share provided by the grid.

The NG consumption of the SOFC CCHP system is calculated by dividing the system's electric power capacity by the electric efficiency and multiplying it by the yearly hours of operation. In cases where a complementary gas heating systems is installed, its consumption should also be considered. The NG consumption of a gas furnace is calculated by dividing its heating capacity by the annual fuel utilization efficiency (AFUE) and then multiplying it with the EFLH of the furnace. For example the NG consumption in a 2000 m^2 apartment block in Vienna comprises of the NG consumed by the SOFC CCHP unit and the consumption of the complementary gas furnace. It is calculated as follows:

$$NG\ consumption\ [MWh/y] = \qquad (37)$$

$$= NG\ consumption_{5\ kWcool\ SOFC\ CCHP} + NG\ consumption_{Furnace} =$$

$$= \frac{El.capacity}{\eta_{el}} * \ EFLH_{5\ kWcool\ SOFC\ CCHP} + \frac{Heat.capacity_{Furnace}}{AFUE} * EFLH_{Furnace} =$$

$$= \frac{28\,[kW]}{0,6} * 8760\,[h/y] * \ 10^{-3} + \frac{70\,[kW]}{0,98} * 2358,9\,[h/y] * 10^{-3} = 577,3\,[MWh/y]$$

The economical part of TCO configuration handles some of the most important parameters like the procurement, installation and maintenance costs of the single components, but also of the systems as a whole. Further the prices and the life expectancy of the stack of SOFC unit are set as well as of the different systems that are implemented and the period of time under review. Here also the prices of the commodities are stated – the price of gas and electricity as well as the ratio between them has a major influence of the systems economic viability. The last important factor that is being handled is the feed in tariff. Because of the SOFC CCHP system continuous operation, a big part of the generated electric power must either be stored or fed to the grid, therefore the feed in tariff plays also a significant role.

5.1.2 Operation Phase

After having considered the procurement and installation costs in the previous phase – the costs that in general occur only once over the product lifecycle, the Operation Phase looks into the expenses that are cumulated due to the operation of the system and are therefore calculated on yearly basis.

The Fuel Cost category summarizes the costs incurred per year from the operation of the system. For a 2000 m^2 apartment block in Vienna with a 28 kW_{el} SOFC CCHP unit and a complementary gas heating system installed, the NG consumption costs are calculated as:

$$NG\ Consumption\ cost\ [€/y] = \tag{38}$$

$$= (NG\ consumption_{5\ kWcool\ SOFC\ CCHP} + NG\ consumption_{Furnace}) * NG\ price =$$

$$= 577,3\ [MWh/y] * 6{,}4\ [ct/kWh] * \frac{10^3}{10^2} = 36.946{,}5\ [€/y]$$

In the same application scenario, no electric consumption costs are incurred, as the fuel cell capacity covers the demand for electric power. Moreover a significant amount of the generated electric power is unused and therefore must be fed to the grid. The profit from the electric power is calculated by multiplying the amount of energy overproduced with the current feed in tariff:

$$Electric\ power\ production\ profit\ [€/y] = \tag{39}$$

$$= Electric\ power\ overproduced * Feed\ in\ Tariff =$$

$$= 167\ [MWh/y] * 8{,}6\ [ct/kWh] * \frac{10^3}{10^2} = 14.362\ [€/y]$$

In this application scenario only 32% of the electric power produced by the fuel cell has been utilized. This means that more than 2/3 of the energy produced had to be given away for only a fraction of the price, what would usually cost us to get it from the grid.

The next category describes the maintenance costs. These are the cost incurred for cleaning and keeping the installed equipment in good working order. These could include for example occasional change of filters, measuring the level and refilling of refrigerant fluid of the air-conditioning system, cleaning operations, general check-ups and adjustments of the system etc. In this thesis the maintenance costs have been estimated as fixed percentages and already calculated in section 5.1.1.3).

The last cost category addresses the costs of scheduled repairs. These costs are more or less predetermined by the current stack life expectancy and the period of time under review. If the observation period is set at 10 years and the current stack life expectancy at 5 years, it means that the stack would have to be changed 2 times over the period of observation. In order to break down these one-time but high stack replacement cost, the stack exchange costs per year are defined. These are calculated by dividing the cost of the stack by the stack's life expectancy. For a 28 kW_{el} SOFC CCHP unit that generates respectively 28 kW_{el} of electric power the cost add up to:

$$Stack\ exchange\ costs\ [€/y] = \tag{40}$$

$$= \frac{Stack\ costs\ per\ kW\ \ * Electric\ power\ capacity}{Stack\ life\ expectancy} =$$

$$= \frac{750\ [€/kW]\ \ * 28\ [kW]}{5\ [y]} = 4.200\ [€/y]$$

That is the sum that must be paid by year for the stack for the operation of the SOFC CCHP system.

5.1.2.1 Cost distribution over lifecycle

In this section, the costs described so far in the previous sections 5.1.2) and 5.1.3) are cumulated over the period of observation, that is set to 10 years. In the beginning the cumulated lifecycle costs are made of the procurement and installations cost of the respective system. With each year of operation, the cumulated lifecycle costs increase by the amount incurred due to the operation of the system, or in other words by the amount of the operational costs. For example the cumulated life cycle costs after the first year of operation for a 2000 m^2 apartment block in Vienna, where a trigeneration system consisting of a 28 kW_{el} SOFC CCHP unit and complemented by an air-conditioning system and a gas furnace are installed are calculated to:

$$Cumulated\ Lifecycle\ Costs\ [€] = \quad (41)$$

$$= Procurement\ Costs + Installation\ Costs + NG\ Consumption\ Costs + Maintenance\ Costs + Scheduled\ repairs\ Costs - Electric\ power\ production\ profit =$$

$$= 64.717\ [€] + 16.273[€] + 36.946[€] + 1.060[€] + 5.600[€] - 14362[€] =$$

$$= 110.235\ [€]$$

This sum represents the overall costs of the system after the first year. The same way it is possible to calculate the overall costs at the end of the observation period for the different system types and application scenarios. However, based alone on the knowledge of these cost it is not possible to make a statement about the economic viability of the SOFC CCHP system. For that reason the delta lifecycle cost were built, which represent the difference between the cumulated lifecycle cost of the SOFC CCHP system and the one of the reference system. By comparing the overall cost of both type of system at the end of the observation it is possible to make a much more justified evaluation of system's economic viability as based only on the procurement costs.

5.1.3 TCO Results

In the last section of the TCO model, the results of this analysis will be graphically presented with the aid of two examples. The first one is the apartment block scenario, where the electric power consumption follows a very inconsistent curve based on the occupancy schedule of the dwellings while on the other hand a strong seasonal dependency is present connected with the heat and cooling power demand. The second example describes the application of the SOFC CCHP system in a server room, where due to the type of operation a constant electric and cooling power demand is present.

5.1.3.1 Apartment Block

The following Figure 5-6 gives a comparison of the cumulated lifecycle costs between the main SOFC CCHP and the reference trigeneration system installed in a 2000 m^2 apartment block in Vienna. In the graph there are three distinct lines. The first - the green one describes the cumulated lifecycle costs of the SOFC CCHP system. The second - the red one also describes the cumulated lifecycle costs of the SOFC CCHP system, but it also includes in the calculation of the revenues from the unused power generated by the fuel cell that is fed to the grid. The blue line shows the lifecycle costs cumulated by the reference trigeneration system. As evident from the illustration, the red and the blue lines cross just after six years of operation, which means that after this period the SOFC CCHP system has been amortized due to its lower operational costs.

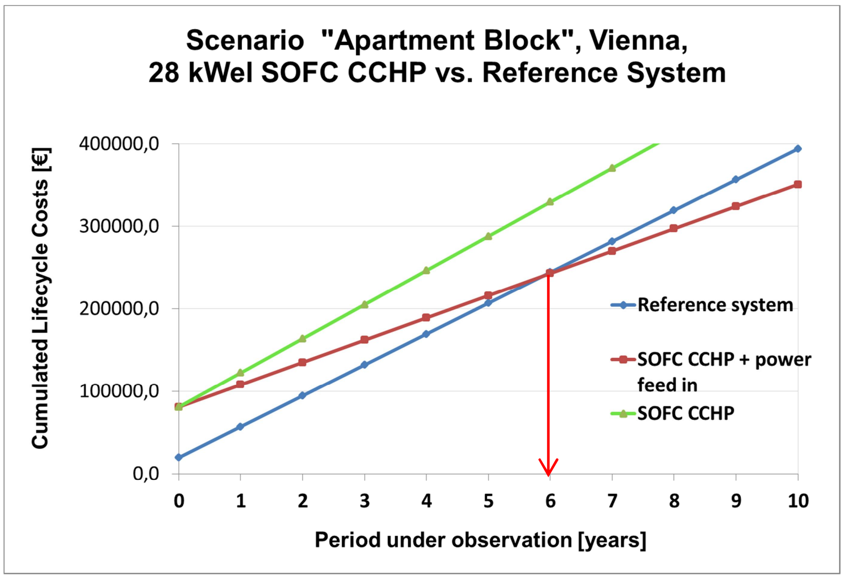

Figure 5-7: Delta Cumulated Lifecycle Costs in an Apartment Block in Vienna[321]

As already stated in course of this thesis, the SOFC CCHP system is a first and foremost an electric power generator. Therefore, for an economically viable implementation a high percentage of the generated electric power should be put to use in the respective application. In this particular application scenario however, due to the occupancy schedule of residential buildings being directly proportional to the use of electric power, the grade of utilization lies at only 32%. This point and the fact that we are looking in the stationary application of the SOFC system with 8760 hours of operation per year, results in an enormous amount of unused electric power that must be fed to the grid. That makes this application scenario particularly dependent on governmental and municipal supports programs and the respective electric power feed in tariffs. This could easily be seen from the figure below, when the two lines describing the cumulated lifecycle costs are compared. When the excess electric power is not fed to the grid, the SOFC CCHP system is no longer competitive to

[321] Own illustration

reference system, as the system has a constant amount of operational costs but its products are not being utilized to their full extent. On the other hand, when the excess electric power is sold for general purposes, then the initially higher investment costs of the SOFC CCCP compared to the reference system would be settled in just 6 years, because of the lower operational costs.

5.1.3.2 Server Room

The second example describes the possible application of the SOFC CCHP system as an electric and cooling power supply of a server room. Because of the similarities of how both systems operate, namely the uninterruptable and constant demand for electric and cooling power, server rooms are by far the most favorable application out of all that have been analyzed. This can be seen also from the Figure 5-7 below, accordingly to which in less than 3 years the initial procurement cost difference between the SOFC CCHP and the reference system will be settled. Moreover, because of the electric power utilization rate reaching almost 100%, as shown in section 5.1.1.4), the system is completely independent from governmental funding and support programs. In application with high electric and cooling demand, the SOFC CCHP system on its own represents a highly attractive possibility for cheap and clean energy production.

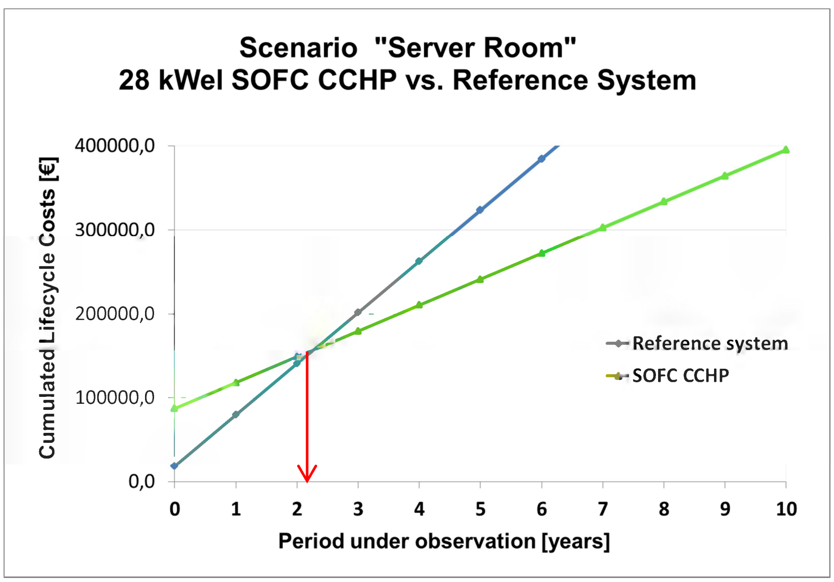

Figure 5-8: Delta Cumulated Lifecycle Costs in a Server Room[322]

[322] Own illustration

5.2 Sensitivity analysis

The sensitivity analysis is a valuable technique that can help to predict the effect of different variables on the system behavior. In the following section, based on the apartment block application scenario, the most influential parameters will be discussed as well as how they affect the economic performance of the SOFC CCHP system.

5.2.1 Geographic location

One of the main parameters determining the use of the combined cooling, heating and power fuel cell system is the respective cooling and heating demand, which are more or less predetermined by the geographic location and the respective climatic conditions prevailing there. The following Figure 5-9 shows how the geographic location could affect the amortization period of the system.

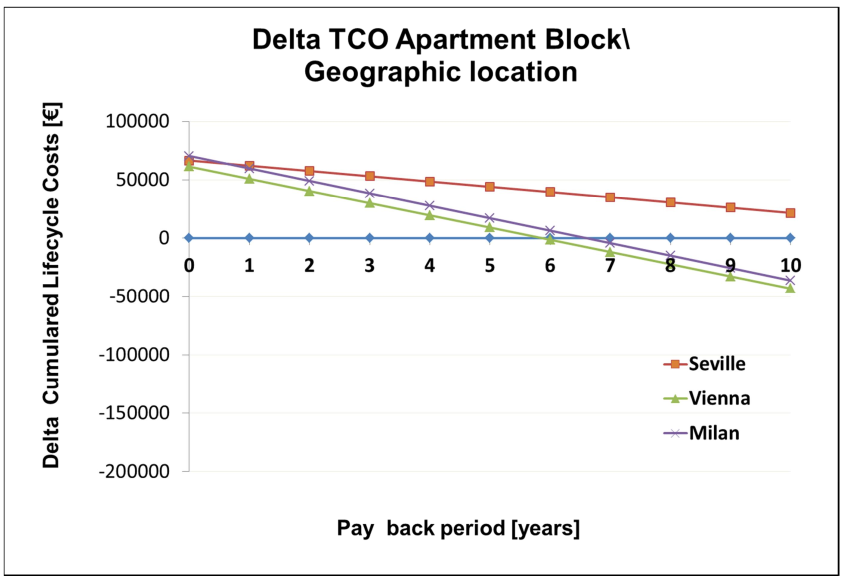

Figure 5-9: Delta TCO of an SOFC CCHP system in different locations[323]

While the base electric load defined as the electric power used for lighting and the electric equipment will be more or less constant for the different locations throughout Europe, the electric and natural gas consumption due to the cooling and heating system can strongly vary depending on the climatic conditions. Because of the SOFC CCHP system's specific cooling to heating power ratio, it can be concluded that in regions with warmer climates like in Seville (Spain) an additional cooling system might be required. This fact does not only lead to higher initial procurement costs, but also to

[323] Own illustration

higher electric power peak consumption that further drives the operational cost over the utilization period. On the other hand, geographic locations with colder climates as the one in Vienna (Austria) will offer much faster payback periods due to the higher levels of heating power utilization, which of course further depends on the utilization of the low temperature heat of the SOFC CCHP system.

5.2.2 Building Area

As the SOFC CCHP system has a lower capacity size limitation, another important parameter worth considering is the size of the building area. This value correlates directly with the electric, cooling and heating power utilization of the system. As it can be seen from the figure below, an apartment block with an area of 2000 m^2 can employ much more of the electric, cooling and heating power produced by the SOFC CCHP module and thus offer a much more efficient utilization of the system, compared to a building half this size. The reason is that the procurement and operational costs of the system grow slightly, while the overall efficiency of the system is doubled and the payback period gets reduced by more than half the time.

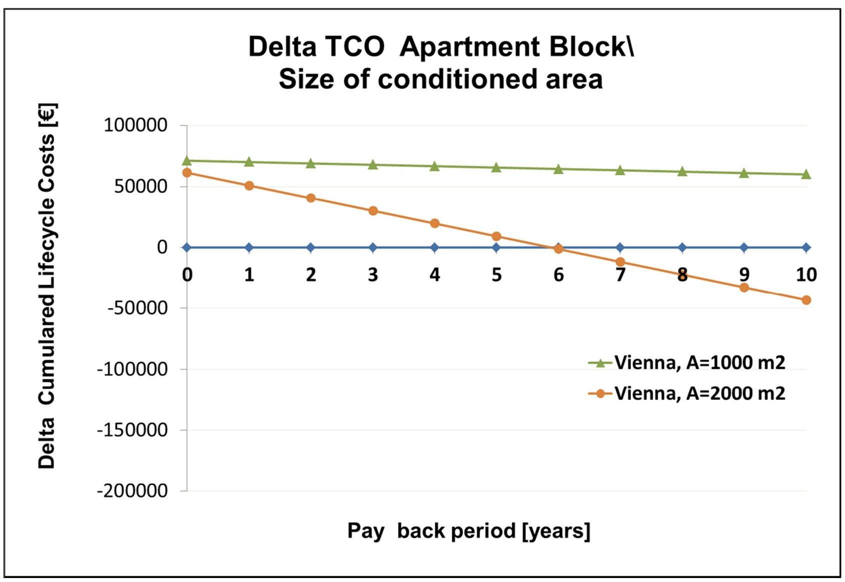

Figure 5-10: Delta TCO of an SOFC CCHP system with different size of the air treated area[324]

[324] Own illustration

5.2.3 Feed in tariff to electric power price ratio

As discussed so far in line of this work, the SOFC CCHP system is a very efficient electric power generating system that is technologically induced to generate a constant amount of electric power over the time of its operation. When the generated electric power could not be fully consumed or otherwise stored, it must be fed to the grid. Therefore, a further specification worth investigating is the price of the electric power fed to the grid or the ratio between the prices of the electric power produced by the SOFC CCHP system and the price of the reference electric power available from the grid. This ratio depends on many factors like the price of oil, the price of natural gas or on the general economic situation, but currently in the European Union it lays around 30%. In application scenarios like the Apartment Block that consume less electric power, a big amount of the produced electric power must be fed to the grid. Therefore a higher feed in tariff would result in a much shorter payback period. As it can be seen from the following figure, a 39% ratio would reduce the payback period from 10 to 6 years respectively, when compared to the current price ratio.

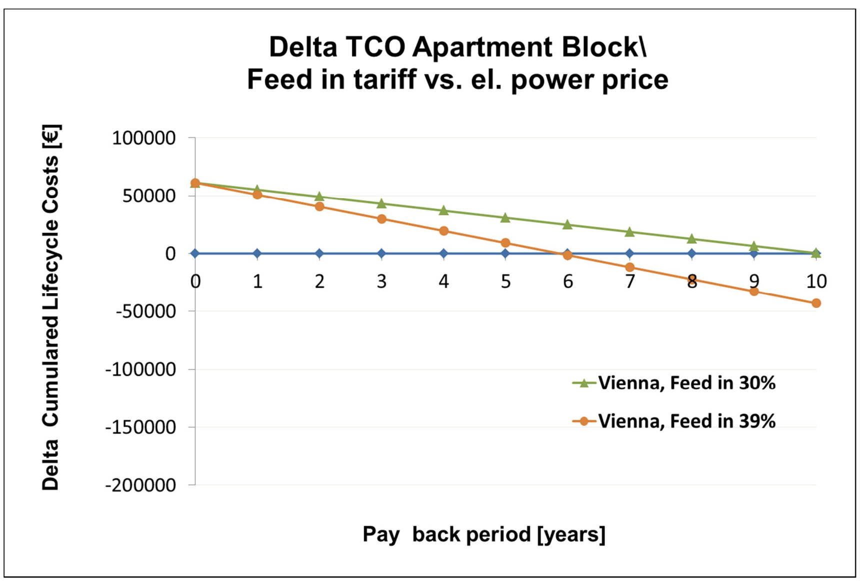

Figure 5-11: Delta TCO of an SOFC CCHP system with different feed in tariffs[325]

5.2.4 Electric power to natural gas (NG) price ratio

Another criterion that might significantly affect the economic performance of the SOFC CCHP system is the price of the commodities. The following Figure 5-11 shows, how

[325] Own illustration

the electric power to the NG price ratio, also known as the spark spread affects the economic performance of the SOFC CCHP system in terms of amortization period.

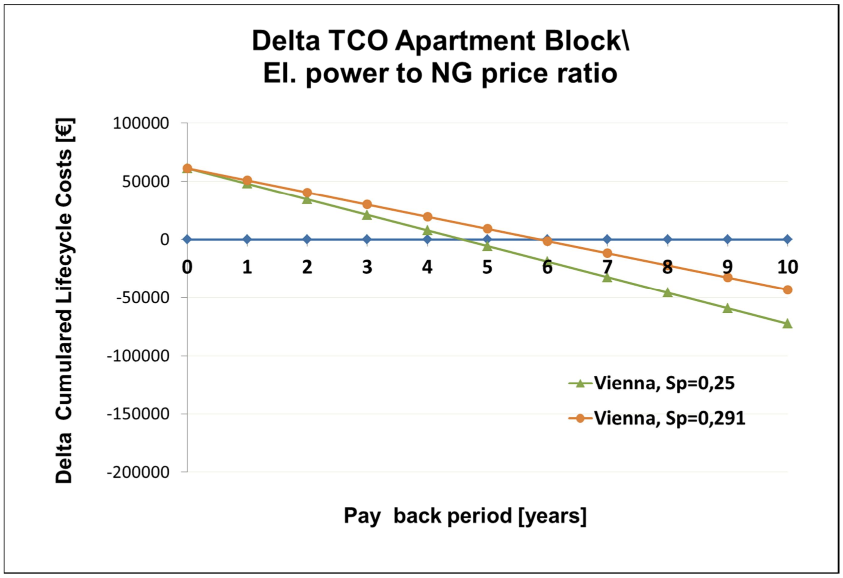

Figure 5-12: Delta TCO of an SOFC CCHP system with different electric power to NG price ratio[326]

Although this ratio has no effect on the direct procurement cost of both systems, it influences the operational costs in terms of fuel costs. Higher fuel costs will result in higher operation costs. From the figure it gets clear that the lower the electric power to NG ratio, the higher the payback period gets and vice versa.

5.2.5 Stack price

As a technologically advanced and still yet not established system the SOFC CCHP system is relatively expensive when compared to the reference electric power generating technologies. A core component of the system and one of the major cost drivers is the fuel cell stack. For this reason, its price has a significant influence to the subjective appeal of the system, as it impacts not only the initial procurement costs but also the technologically induced operational costs. As it can be seen from the following figure, a possible stack price of 500 EUR per kW does not only drive down the procurement cost but could also reduce the payback period by more than two years, when compared to a stack price of 1000 EUR per kW.

[326] Own illustration

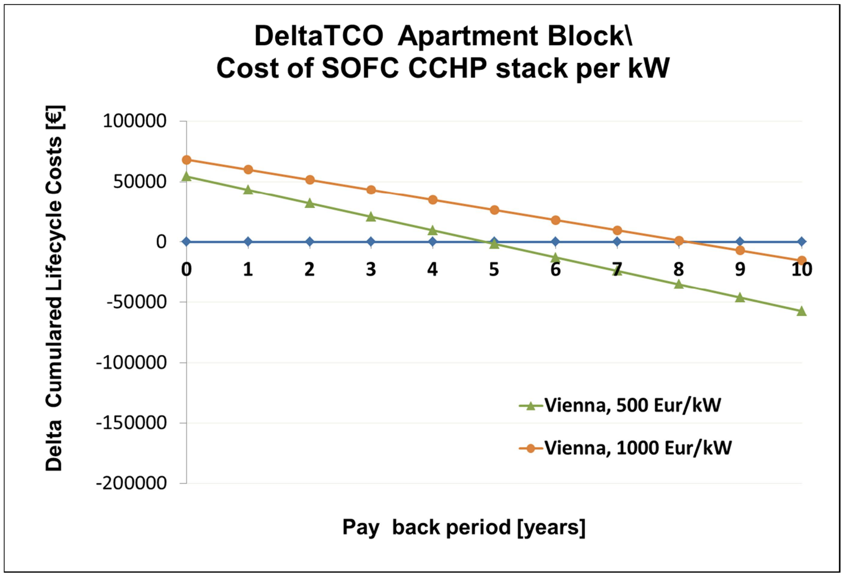

Figure 5-13: Delta TCO of an SOFC CCHP system with different stack prices per kW_{el} capacity[327]

5.2.6 SOFC CCHP electric efficiency

One of the main advantages of the SOFC technology is its higher electric efficiency compared to the conventional thermo-mechanical electric power generating systems. The following figure illustrates how it can affect the economic performance of the system.

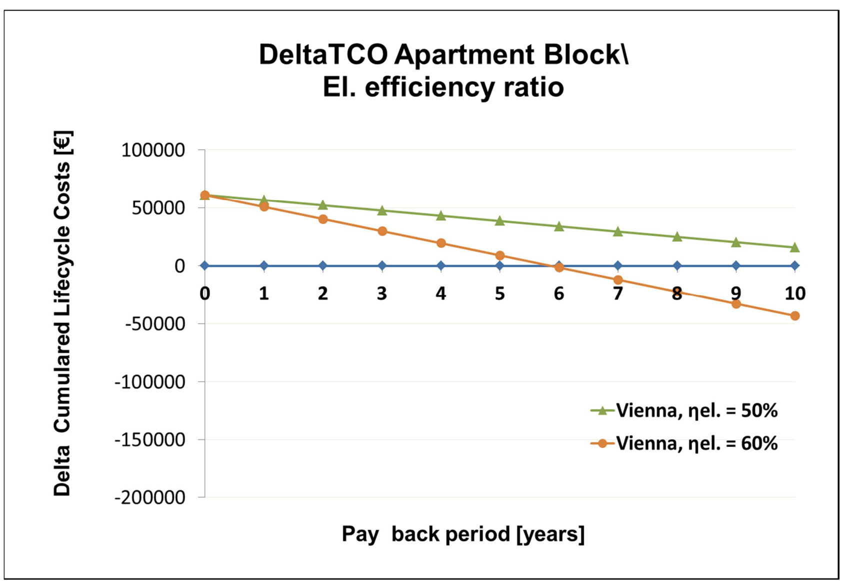

Figure 5-14: Delta TCO of an SOFC CCHP system with different el. efficiency[328]

[327] Own illustration

As evident from the Figure 5-13, a change of the electric efficiency ratio from 50% to 60% can have a massive effect on the system overall economic performance. This improvement would not affect the initial procurement costs, but would significantly shorten the payback period of the system, due to the much more efficient use of the systems resources. In other words, with the same input e.g. natural gas, the system will provide 10% more of the output being the electric power and therefore the entire system could amortize in much shorter time period.

5.2.7 Electric to cooling power ratio

When operating in cooling and heating mode, the SOFC CCHP system provides 5 kW_{Cool} of cooling, 16 kW_{Heat} of heating and 28 kW_{el} electric power, which results in a fixed electric to cooling power ratio of 5,6. For application scenarios such as the apartment block, where a moderate electric consumption is present - a big part of the electric energy would not get utilized and therefore must be fed to the grid. On the other hand, a lower electric to cooling power ratio of about 4, will result in lower electric power output and therefore to a better electric power utilization of the fuel cell. Moreover a smaller SOFC CCHP stack will lead to lower procurement costs and a faster payback period because of the reduced operational costs

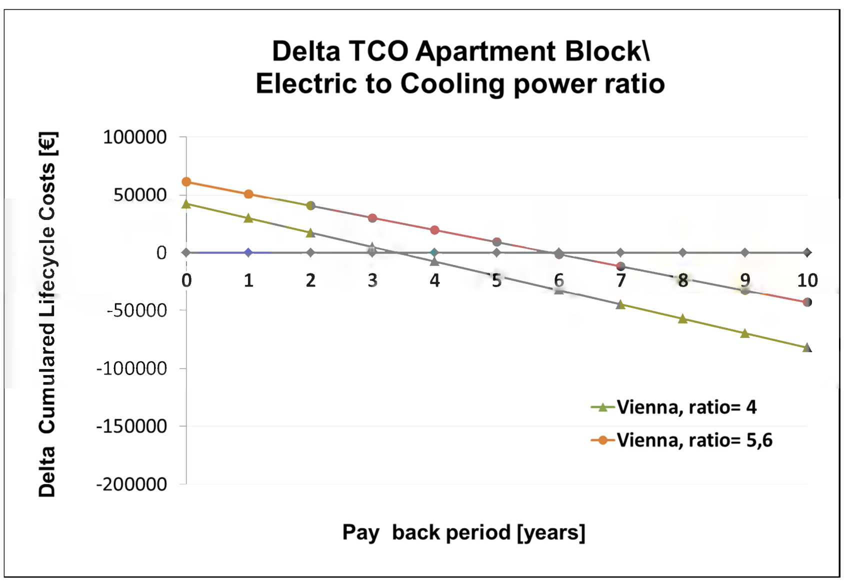

Figure 5-15: Delta TCO of an SOFC CCHP system with different electric to cooling power ratio[329]

[328] Own illustration
[329] Own illustration

As it can be seen from the Figure 5-14, a smaller electric capacity of the SOFC CCHP system, leading to a smaller electric to cooling power ratio, will not only reduce the initial procurement costs, but also reduce the payback period by almost 50%.

5.2.8 SOFC CCHP Heating power

The last criterion to be addressed is related to the heating power capacity of the SOFC CCHP system. As previously stated, the heating capacity measures 16 kW_{Heat} and it comprises 3 kW_{Heat} coming from the utilized exhaust gases of the fuel cell at about 100°C and 13 kW_{Heat} that are discharged from the absorption chiller during the cooling process at about 35°C. However, because much of the heating power provided is at a low temperature level, question arises if this amount could be used for heating purposes at all. Therefore two cases are distinguished - the one with 3 kW_{Heat} and the second one with 16 kW_{Heat} of usable heating power, while in both cases the same amount of fuel is consumed. As it can be seen from the following Figure 5-15, the initial costs would differ only slightly, contrasting to the payback period. The main reason for such a development is that in the case of the smaller available heating capacity an additional heating system will be needed and due to the added operational costs for fuel and maintenance, a longer payback period is to be expected.

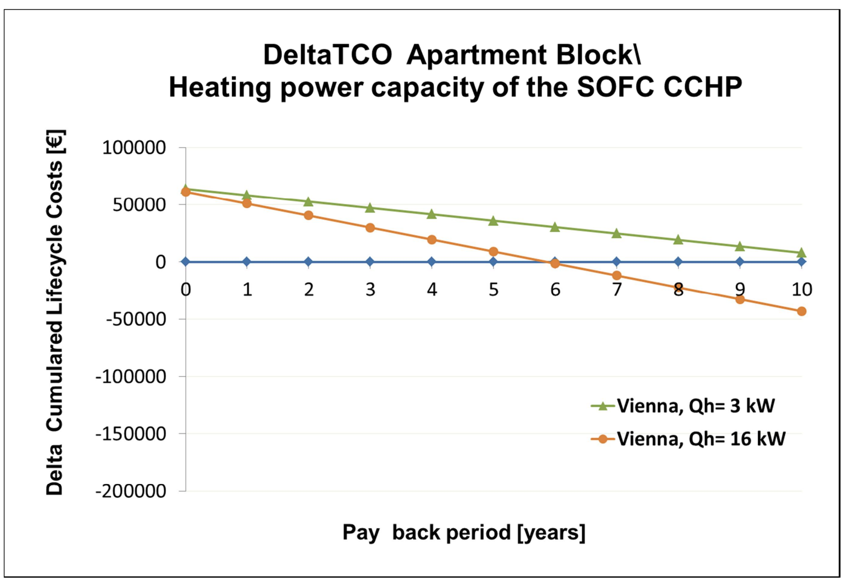

Figure 5-16: Delta TCO of an SOFC CCHP system with different heating power capacity available[330]

[330] Own illustration

5.3 Conclusion of the economic analysis

The comprehensive economic study of the SOFC CCHP system brought out some interesting results. Unsurprisingly, as best application of the system turned out to be the data center, which because of its uninterruptable electric and cooling power demand was the best fit for the system and managed to utilize most of its energy output. The TCO model showed that even without employing the available heating power, the system was able to amortize in less than 3 years, when compared to the reference system that used an air-conditioner and electric power from the grid. On the other hand, in applications scenarios where less electric power is consumed - like the office building or the apartment block, the utilization of the available heat is required for an economic viable application. In applications like this, it takes on average 6 years for the complete amortization of the system.

In the sensitivity analysis it was possible to identify the key parameters that influence the economic performance of the system. On first place is the size of the conditioned area. As the SOFC CCHP has a lower capacity limit, an area of at least 2000 m^2 is required, so that a reasonable amount of the produced energy could be utilized and the system could be amortized. Another parameter of key importance is the technology advancement of the fuel cell. The higher the efficiency level of the fuel cell, less fuel it would consume and the cheaper the electric power would get. A further parameter worth mentioning is of course the stack price. Because the fuel cell systems still have not reached mass production levels, the stack remains the main cost driver of the systems. Combined with the relatively short life expectancy of the stack of about 5 years and the related stack exchange costs, mean that small improvements in the price could dramatically reduce both the initial procurement costs as well as the operational costs of the system and thus make it more appealing to the mass customer. One last important parameter is of course the feed in tariff rate. As most applications are not able to fully utilize the electric power produced by the system, a big part of it must be fed to the grid. In the current market situation apart from the data center applications, the rest of the studied scenarios are strongly dependent on the rate of the feed in tariff, as it is the only factor that could guarantee the viability of the system.

6 Conclusion and Outlook

The following master thesis was written in cooperation with the AVL List Company with the goal to identify realistic applications of AVL's SOFC CCHP system and evaluate their operation in comparison to the reference systems on the market. In the first chapter of this thesis, a short description of the AVL List Company was given, followed by an evaluation of the initial situation and a definition of the goals of the master thesis.

In the second chapter, based on a broad literature review the theoretical foundations were set, and the components of the SOFC CCHP system were discussed in detail. The focus lies on the technical side of the problem and explores in detail the operating principle of the SOFC CCHP system and its components as well of the system used as a reference.

With the third chapter begins the practical part of the master thesis. This chapter begins with the investigation of the possible stationary applications of the SOFC CCHP system, followed by the respective market potential analysis. However, as no real trigeneration system providing electric, cooling and heating power simultaneously has yet been successfully implemented on the market, the estimation of the SOFC CCHP market potential has proven to be very challenging. A further limitation was the lack of appropriate data on this topic. In order to achieve some results, a very conservative approximation of the possible market potential has been made based on the assumed electric power demand of the identified application field, while also considering the real data coming from the market sales of central air-conditioning products below 20 kW cooling capacity.

In the next chapter the system costs of the SOFC CCHP unit were estimated. The cost of the system were calculated as a function of the production volume per year and were calculated first for the two system components separately and then for the entire system as a whole. For the fuel cell, the target cost of 2000 Euro/kW for 5000 units per year, stated by the AVL were adopted. For the absorption chiller on the other hand, a cost degradation model was setup using a learning curve model and the available market sales data from different producers as a base. In this case, the costs calculated with the learning curve model could be seen as guide values, as in this cooling capacity and temperature level segment no absorption chillers in serial production exist.

The last chapter represents the core of this master thesis and it delivers a detailed description of the Total Cost of Ownership model, designed specifically for the stationary applications of the SOFC CCHP system. The Excel based tool comprises and calculates all possible cost that could occur over the lifecycle of the SOFC CCHP and the comparable reference trigeneration system. As a result the TCO tool delivers an amortization calculation of the SOFC CCHP system that could be used to answer the economic viability question of the SOFC CCHP system. Based on the knowledge gained from the TCO tool it could be concluded, that the most important factor that determines the performance of the system is the utilization grade of the electric power generated by the SOFC CCHP system, due to the electric to cooling power capacity ratio of the system. System with high utilization rates of the generated electric power tend to amortize faster than systems with lower ones. Further in this chapter a sensitivity analysis was conducted that helped to identify the most crucial parameters influencing the SOFC CCHP system performance.

The economic study of the SOFC CCHP system carried out in the master thesis on hand is very theoretical one and it is based on a fair amount of assumptions. Therefore it could be seen as a preliminary concept and a good base for future research on this topic. The next obvious step would be a more detailed economic analysis of the applications that has been identified as the best fit and actual trial runs of the prototype SOFC CCHP system that could verify the results obtained from the simulation of the developed TCO tool.

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8 List of Figures

9 List of Tables

10 List of Abbreviations

AC	Alternating current
AFC	Alkaline fuel cell
b	Slope of the learning curve [%]
Btu	British thermal units
CCU	Close control unit
CFS	Chloro-fluorocarbons
CHP	Combine heat and power
COP	Coefficient of performance
CRAC	Computer room air-conditioner
CV	Constant air volume
DMFC	Direct methanol fuel cell
DX	Direct expansion system
EER	Energy efficiency ratio
GDP	Gross domestic product
HCFCs	Hydro-chlorofluorocarbons
HFSs	Hydro-fluorocarbons
K	Algebraic midpoint of a production lot
MCFC	Molten carbonated fuel cell
m_{fc}	Exhaust gas mass flow rate [kg/s]

N	Number of units produced
NG	Natural Gas
PAFC	Phosphoric acid fuel cell
P_{el}	Electric Power [W]
PEMFC	Proton Exchange Membrane fuel cells
Q_{Con}	Heating power of Condenser [kW]
Q_{Eva}	Cooling power of Evaporator [kW]
SOFC	Sold oxide fuel cell
SOFC CCHP	Solid oxide fuel cell combined cooling heat and power
t	Temperature[°C]
T_1	Time to produce the first unit [h]
$t_{chilled}$	Temperature of chilled water [°C]
TCO	Total cost of ownership
t_{cool}	Temperature of cooling water [°C]
T_K	Midpoint unit
T_N	Time to produce the n-th unit [h]
VAV	Variable air volume systems
VRF	Variable refrigerant flow
W	Work [kJ]
η_{el}	Electric efficiency fuel cell [%]

$\eta_{Sys,Cool}$	Overall efficiency SOFC CCHP system combined cooling and power generation [%]
$\eta_{Sys,Cool+Heat}$	Overall efficiency of the SOFC CCHP system combined cooling, heating and power generation [%]