SIMULATION OF SOFC-BASED MICRO-COMBINED HEAT AND POWER SYSTEMS IN RESIDENTIAL APPLICATIONS

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ABSTRACT

The successful deployment of fuel cell-based micro-combined heat and power (mCHP) systems in the 1-10 kW scale for residential and light commercial applications faces substantial market challenges. In addition to the hurdles of low first cost, low maintenance, proven durability and robustness, fuel cell-based mCHP faces competition with renewable resources such as solar photovoltaic and solar thermal systems, as well as the continuing challenge of low-cost grid electricity. Furthermore, early mCHP market technology penetrators in Europe and Japan have been largely based on internal combustion engines. The present study explores the application of optimized, natural gas-fueled solid oxide fuel cell combined heat and power systems in both single-family detached dwellings and light commercial buildings. Building loads and energy costs of four different geographic areas are presented and simulation of an SOFC system against the various building energy demands is performed to provide a techno-economic evaluation of the technology. Results related to SOFC operating strategies, system "right-sizing," the match between end-use and mCHP system thermal-to-electric ratios, and emission characteristics are presented with an aim towards identifying the overall viability and necessary application requirements for successful deployment of the technology. Emission levels are found to be substantially lower than those associated with grid-electricity generation, however, the viability of SOFC technology is found to be strongly correlated with the price difference between natural gas and grid-electricity. Climate conditions at one of the considered geographic locations is similar to Polish conditions. Although, gas and electricity prices in Poland are different than at the American market, the results of the study illustrates circumstances for a future development of the SOFC-based mCHP systems in Poland.

PREFACE

The object of this work is a performance of high efficiency solid oxide fuel cell based micro-combined heat and power system. The project goal is to simulate and analyze an advanced solid oxide fuel cell combined heat and power system in a residential application. This is very important because the high efficiency system power generators have lower CO_2 emissions. It is very important to increase the efficiency at a possibly low cost, which can be obtained through the SOFC-based mCHP. They are also perfect for small residential applications. These systems are very promising because there is a huge market for them in the USA as well as in Poland. This project provides information about the most suitable place for such systems. The results will also give the answer if such a system is economically efficient and what kind of advantage it would have over conventional technology.

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1 INTRODUCTION

1.1 Importance of micro-CHP

Combined Heat and Power(CHP) generation is an efficient method for transformation of chemical energy into electricity and heat. Heat and power generating plants, of big and small capacity, based on steam or gas cycles, are well known and established. They operate with high efficiency and availability. Micro combined heat and power units (mCHP) are not known so well. Those units are of a capacity from 1 to 10 kW and are designed to meet the needs of a single-family house or a small commercial building. mCHPs are in the phase of development or at the beginning of entering the commercial market. Up to 2004, early mCHP units were mostly installed in Germany and Japan [1].

Many countries have to lower their greenhouse gasses emission. This can be done by increasing the efficiency of generation and distribution of energy produced in centralized units, application of more efficient combined heat and power unit, and wider use of renewable energy sources. CHP units due to their very high efficiency are more environmentally sound than units producing electricity and heat in separate processes. The efficiency of electricity generation at sub-critical steam power plants is about 35% (LHV) [2] and waste, low-temperature heat from the process is released to the atmosphere. In the cogeneration mode waste heat taken back from electricity generation process is converted into useful heat carriers. Better fuel usage due to heat recovery, results in higher efficiency and lower CO_2 emissions.

Micro combined heat and power systems are considered as distributed power generation. It provides power to the end user avoiding costs of electricity transmission and distribution. This makes mCHP units more competitive on the market. Costs of transmission and distribution have been growing rapidly since 1970 and are now at a level of production cost [3]. Such a situation occurs due to environmental considerations and the high cost of access to the infrastructure. It is also important that mCHP systems can provide customers with an uninterrupted power supply and high power quality.

The electricity market is enormous. It is hard to imagine what our life would look like without electricity. In the residential sector we use 27.4% of total electricity consumption of the world, which is 4.6 PWh [4]. In the United States, the share of the residential sector is higher than average and reaches 36.2% out of 3.8 PWh, in Poland it's just 23% of the share in national electricity consumption [4]. We can confirm that electricity fulfills important role and can be account alone as a big market. In United States, Canada, Europe (except Southern European countries), and in Russia, dwellings requirements for electricity are lower than requirements for heating during winter season[5]. This indicates that heat consumption in the residential sector is also very high and important. Those two facts expose a special market for micro-combined heat and power.

The micro combined heat and power market is quite new but with a great potential. In 2004 over 12,000 mCHP unit were sold all over the world to homes and small commercial buildings[1]. It is predicted that the sale will growth and will depend mainly on the success of products that have already entered the market. Almost all of those units are based on the internal combustion engine. Fuel cell based mCHP units have not

entered the market yet although some fuel cell developers are really close to it [6]. Producers expect that the North American market of mCHP units will consist of two big sectors[1]. The first of them includes small business and high-energy-consuming houses, and the second one is an off-grid houses sector. The first is tempting due to easy optimization and possible economic visibility as a heat-led device. The micro combined heat and power unit installed e.g. at a house with a swimming pool, which has a high heat demand, will also have high operative hours. The other market, which is the off-grid houses sector, is promising due to fact of consumers' willingness to pay more for access to energy in the form of heat and electricity.

Fuel cell-based micro combined heat and power units are really promising due to the above-mentioned above high energy conversion efficiency, and also for good scaling of those systems for distributed generation. Moreover fuel cells have also low chemical, thermal and acoustic emissions. For some customers, an important feature of technology is the fuel flexibility, which is possible for fuel cells. All these advantages of fuel cells make them really good power generators. The only problem with fuel cell based mCHP systems is that the fuel cells themselves are still in a phase of development and still have very high investment costs.

1.2   Application considerations

Four different locations have been selected in this thesis for consideration of a SOFC-based micro combined heat and power application. Some of these locations have a similar climate to weather conditions in Poland. These are Baltimore, Madison, Phoenix and Tampa Bay area.

The first location is Baltimore, which is situated at the East cost of United States in the state of the Maryland. The climate of Baltimore is classified as humid subtropical. The coldest month is January and the hottest is July. The temperature varies between 26.9 and 1.6°C[7]. Average monthly precipitation is around 8.1 cm[7]. Relative humidity in Baltimore is changing during the day on average from 77% in the morning to 54% in the afternoon[7]. Morning highest humidity is during the summer time. It also drops to the lowest in the afternoon. During winter season, the humidity amplitude is not so high as in the morning. It is around 74% and it drop to just 54 - 57%[8].

The next location is the town of Madison in Wisconsin. The climate of Madison is known as a humid continental climate. It is characteristic that the temperature has big seasonal variance and weather patterns are also variable. During the summer season the temperature is around 21°C and during the winter it goes down to -8°C. The average monthly precipitation in Madison varies through the year between 3.2 cm up to 10 cm[9]. The average relative humidity is 83% in the morning and 64% in the evening. The changes of relative humidity are similar to those at Baltimore. During the summer the relative humidity reaches 91% and drops to 64% and in winter it is around 79%-82% in morning and 67%-80% in evening[8].

A much warmer location is Phoenix in Arizona, which has a subtropical arid climate. The temperature during the summer is between 23 and 40°C and during the winter it does not drop below 6°C rising even to 18°C. The precipitation in Phoenix is really low. The maximal monthly average is just 2.7cm[10]. The humidity in Phoenix is also very low. On average in the morning it reaches 50% and drops during the day to 23%. It also has a completely different pattern from Madison and Baltimore. The lowest humidity level is in May and June when in the mornings it reaches 35%-30% and drops to 14%-

12%. The highest relative humidity is during winter when it reaches 65% and does not drop below 32%[8].

The last from the four chosen locations is the Tampa Bay region in Florida. The climate in Tampa Bay is humid, subtropical. The monthly average temperature during the year varies between 16 and 27°C. The precipitation is also higher than in Phoenix and fluctuates between 4.1cm and 19.3cm[11]. The relative humidity through the year period is quite constant. In the morning it is between 85% and 91% and on average is about 88%. Also the afternoon monthly average of relative humidity is relatively constant and is between 52 and 65%. The year average relative humidity in the afternoon is 59%[8].

The Polish climate is a combination of the oceanic and the continental climates. Because of this mix of climates, seasons can be rather dry or wet depending on air masses. The monthly average temperature during the year is about 19°C during the summer and from -6 to 0°C in the winter[12]. Yearly precipitation in Poland is around 750mm. Most of precipitation occurs during the summer season, and during the rest of the year precipitation is on a similar level[12]. The relative humidity varies with geographic location, and in central and southern Poland it is between 77% to 81%. In the north Poland it reaches 85%[13]. All of the climate indicators for Poland are similar to the climate characteristics in Madison. The temperature variations are almost the same. The precipitation in Madison is only a bit smaller than in Poland. The relative humidity which is on average between 85% and 77% in Poland is similar to this in Madison.

Residential buildings of the same characteristics were considered in all the chosen locations for the present study. The dwelling-place of 200m^2 area, inhabited by four persons was taken into account. The average exchange of air was assumed at 0.75 per hour. Comparison between loads for similar residential unit in different climate zones makes the case study more precise. The same dwelling features makes it possible to understand the climatic impact on the load requirements and performance of the system.

Load requirements for all these locations consist of electric-, heat-, cooling-load and domestic hot water demand. The electric load is a sum of base electric load, which is assumed to be equal at all of the chosen locations, and electricity load consumed for space cooling. It was also accepted that a year is divided into a heating and a cooling season. Duration of the both seasons depends on the location. The longest heating season is in Madison area and the shortest occurs in Phoenix. An assumption was made in this thesis that during the heating season only heating loads occurs and there are no space cooling requirements. A similar rule concerns the cooling season. The based domestic hot water loads was assumed to be equal every day. The exact value of it depends on the ambient temperature. All loads requirements were precisely described in next chapter.

Each combined heat and power application can be described by its thermal to electric ratio (TER). It can relate to produced or consumed thermal energy. The ideal system has similar TER of production and consumption. This indicates how well the application is matched. The precise description of TER for heating and cooling demands is given in the following chapter.

The economic performance of SOFC mCHP system depends on the operation mode of the system as well as on the costs of utilities. In this work prices of electricity are based on official web sides of electric companies operating at the chosen location. The prices are given for 2010. At some sites more than one tariff schedule was taken into account.

Usually electricity rates consist of a customer charge, paid on a monthly basis. The second tariff component is an effective rate which depends on the time of a day, season and on the total energy consumption. In Tampa Bay area the customer has to pay the fuel cost, environmental cost and others. Tariffs in different locations vary from one from another mostly in the effective rate. The effective rate may depend on time or may be constant during the day and night.

The assumed gas prices refer also to websites of energy companies operating at the given locations. The customer pays a fixed and a variable charge. The fixed charge is constant throughout the year and is expressed in dollars per month or day. The variable part is an effective rate paid for the gas consumed. That price is given in dollars per therm, where therm is 100,000 Btu. Gas prices are also given for 2010.

Depending on the system operation mode, the solid oxide fuel cell might produce more electricity than it is required to cover the building demand. In that case the excess electricity is directed to the grid. Such a system requires an additional restriction which will regulate how this energy is included in the electricity bill for the household. The gas and electricity prices, and net metering rates are specified described in the next chapter.

1.3   mCHP technology comparison

Up to now micro combined heat and power units of the capacity in a range of 5 to 10 kW have been sold in Japan. Also a small number of 1 kW units have been brought into that market. In Europe 5 kW units are sold mostly on the German market for households and commercial buildings. 1 kW mCHP systems for households have been introduced in UK. Only a small number of 5 kW units have been sold to the users in North America. Applications of the mCHP unit as well as ongoing prototypes are presented at the table 1-1[1].

Table 1-1 Micro-CHP installations up to 2004[1]

Micro-CHP systems being sold to customers on a commercial basis			Micro-CHP units being installed and run on a field-trial basis		
Manufacturer	Size and type of unit	Sales	Manufacturer	Size and type of unit	Installations
Japan					
ECOWILL	1-kW gas engines	Around 3,000 units have been sold to homeowners and housing developers	Various fuel cell developers	1- to 5-kW fuel cells	Mainly led by gas utilities, with dozens of trial installations in homes, apartment blocks, and small commercial businesses
Yanmar, Aisin Seiki, and Sanyo	5- to 10-kW gas engines	Several hundred units have been sold to small commercial businesses			
Europe					
SenerTec	5-kW gas engines	More than 8,000 units sold, mainly in Germany, to small commercial businesses as well as to multifamily and single-family households	Sulzer Hexis	1-kW fuel cells	More than 100 installations, mainly in homes and primarily in Germany
Ecopower	5-kW gas engine	Around 500 units have been sold, mainly in Germany, to small commercial businesses as well as multifamily and single-family households	Vaillant	Built around Plug Power's 5-kW fuel cell	Around 40 installations in multifamily housing and at small commercial businesses
Whisper Tech	1-kW Stirling engines	About 400 Whisper Tech systems are being sold by a UK utility in the first half of 2004 to homeowners and housing developers	BG Microgen	1-kW Stirling engines	Several units are being tested in UK homes
			Enatec	1-kW Stirling engines	Several installations in households in the Netherlands
North America					
VectorCogen	5-kW gas engines	Around 15 units were installed in 2003 in large homes and small commercial businesses	Plug Power	5-kW fuel cells	Dozens of installations in homes and small commercial businesses

The most common mCHP technology is based on internal combustion engines(ICE). Although they are very well known there is still a problem with a noise and pollutant emissions, and with maintenance. The cost of a small capacity CHP based on the ICE system is around $2,700/kW [1]. Internal combustion engines have a number of advantages such as the mature, well-understood technology, and the possibility to supply with a variety of fuels. Apart from the earlier listed disadvantages, it is significant that the ICEs cost increases rapidly as the unit size of unit decreases and it can be reduced only through higher-volume manufacturing.

Another already commercially available mCHP technology, is the Stirling Engine(SE) system. The key problems with the SE manufacture and application are connected with materials, seals and NO_x emissions. The material used for the SE construction has to withstand high temperature near to the burner (if fuel combustion is the source of the process heat). The working gases which operate at high pressure must be sealed. The possibility of NO_x formation is due to the high temperature of the burner operation. Another disadvantage of SE is the very low electricity generation efficiency limited in practice to around 10 – 15% [1]. The positive features of Stirling Engines are the low noise level and almost no maintenance.

The Rankine Cycle Engine (RCE) is a well-established technology at large and a medium-scale but is just entering the market of mCHP systems. At the RCE, high pressure superheated steam expands in the turbine generating mechanical power, and then it is condensed. The condensate water is pumped and heated, and again the pressurised and superheated steam is generated. Recently some companies such as Cogen Microsystems and Energetix developed a micro-RCE technology and are in the phase of tests [14,15]. Also Lion Powerblock, a German company, already manufactures and sells theirs Rankine cycle-based micro-CHP units [16]. The

advantages of RCEs systems are: use of conventional burners, flexibility between heat and electric power generation, and very limited maintenance. The disadvantage of those micro-units is the very low electrical efficiency [1] around 10% [14,15,16].

The fuel cell technology considered as a basis for mCHP is a proton exchange membrane (PEM) fuel cell. In PEMFC hydrogen and oxygen create water and electric power in an electrochemical reaction. PEM fuel cells still need a lot of improvements in many matters. The main issues which need amelioration are: short lifetime, high cost and auxiliary power consumption. Other disadvantages of the PEMFC system are: a big number of additional components, intolerance to carbon monoxide and sulphur as well as limitation to one fuel type. It is also hard to recover heat from the PEM fuel cell due to the low stack temperature. Apart for that, PEM fuel cells have a lot of advantages such as no moving parts other than pumps and funs, fast start up, negligible emission of NO_x and the possibility of part-load operation.

The next fuel cell technology used in a mCHP system is the solid oxide fuel cell (SOFC). This type of fuel cell differs significantly from the PEM FC. The construction of the SOFC can be planar or tubular. SOFCs are built with the use of a ceramic material. A yittra-stabilized zirconia(YSZ) is used as an electrolyte and other ceramic materials are applied for the cathode and anode. In the SOFC, the moving ions are oxygen ions. To enable ion infiltration the solid electrolyte of the SOFC is working at a under high temperature of $700 - 1000°C$ [17]. Due to the high operation temperature the solid oxide fuel cells, are more tolerant to fuel impurities and can run supplied both with hydrogen and carbon monoxide. However, high temperature causes high stress in both cells and stack materials. There is also a problem with planar SOFCs sealing. Although SOFCs have been tested for a long time, that kind of fuel cells is still unavailable on the market. The disadvantages of SOFCs are: requirements for natural gas pre-treatment, use of delicate ceramic materials for cell construction, long start-up and shut –down time, and necessity of effective thermal insulation. Moreover, SOFCs required auxiliary equipment such as heat exchangers, blowers, pumps and inverters. Despite many disadvantages, SOFCs are attractive systems due to high electric efficiency (from 25 to 40% and more), simpler fuel reforming, no moving parts exept pumps or funs and almost zero NO_x emission.

Table 1-2 Main mCHP technologies [1]

Technology	Electrical efficiency (%)	Approximate heat-to-power ratio	Development status	Projected commercial availability for micro-CHP applications	NO_x emissions	Fuel treatment	Noise (dBA at 1 meter)
Solid oxide fuel cells	25 or better; possibly higher than 40	Between 1:1 and 2:1	Field tests	Toward the end of the decade	Negligible	Requires partial reforming to extract hydrogen and carbon monoxide	65 or quieter; the only noise is from fans and pumps
PEM fuel cells	25 to low 30s	Around 1.8:1 to 1.3:1	Field test	Commercial sales targeted for 2005–2006 in Japan; likely to start elsewhere toward the end of the decade	Negligible	Requires full reforming to extract hydrogen and remove carbon monoxide	60 or quieter; the only noise is from fans and pumps
Stirling engines	10 to 20s	Typically 6:1 to 8:1	Commercially available in the UK and some off-grid markets	Being sold commercially	Depends on type of burner; two developers say <30 ppm, and <3 ppm with a ceramic burner	Run directly off natural gas or other fuels	Around 44 for the quietest units
Rankine cycle engines	Around 10	8:1 to 10:1	Prototypes developed	Field tests planned for 2004–2005, commercial availability to follow shortly after	As low as 10 to 20 ppm	Run directly off natural gas or other fuels	Not known, developers' targets are similar to noise from a boiler or furnace
Internal combustion engines	20 to low 30s	1.3:1 to 2.2:1	Commercially available	Being sold commercially	High if uncontrolled, but using catalysts or lean burn can be as low as 10 to 20 ppm	Run directly off natural gas or other fuels	Can be attenuated to as low as 44 for a 1-kW unit or to the mid 50s for 5-kW units

In table 1-2 all of the technologies are listed.

Fuel cells are a promising technology for future electricity and heat production. They are very efficient power generators, and have advantages of both heat engines and batteries[18]. A big advantage over internal combustion engines and batteries is the possibility of scaling in a very wide range. Micro combined heat and power units based on the solid oxide fuel cell are expected to have almost zero NO_x and SO_x emissions. Fuel cells are quiet in operation and if used as distributed power sources they eliminate the costs of electricity transmission and distribution. Moreover they operate well both with the nominal and a partial load. The efficiency characteristic increases with the load decrease unlike in other conventional systems. Although, mCHP systems are good and some of them ready for entering the market only in Japan the mCHP unit are installed.

1.4 Thesis objectives and approach

The objectives of the thesis are:

- Evaluation of how well SOFC-based micro-CHP systems can meet the total building energy demand.
- Determination of the system's technical and economic performance sensitivity to different parameters such as TER, loads and other.
- Recognition of economic conditions for which the SOFC application will be economically viable.

A mathematical model of the SOFC-based mCHP will be used for optimization of the SOFC application in four different geographical locations. It will also indicate what location would be the best to adopt such system. The mCHP system analysis will also include evaluation of operation strategies, such as load following versus nominal output. The computation results can also confirm if it is possible to meet the chosen residential demand for heat and electricity with the optimum system, chosen on the basis of economics. This can be difficult to obtain due to different levels of power demand during the year, and it may be impossible to adjust one size of the mCHP system when the technical optimum for the geographical location and load requirements are found. The results should be helpful for indication of parameters which make the SOFC based mCHP system economically attractive for the micro-cogeneration market. Finally conclusions and recommendation for future work will be drown from a wide analysis of the mCHP system.

Four main variables are taken into account in at the study. The first one is the size of the mCHP system. 1, 2, 3, 5 and 10 kW systems were taken under consideration. The second variable is the location where the mCHP unit based on SOFC would be applied. The four considered locations are, as it was already presented, Madison in Wisconsin, Baltimore in Maryland, Tampa Bay in Florida and Phoenix in Arizona. The third determinant is the operation mode. The operation of the mCHP based on SOFC is analyzed at all four sites, for the whole above-mentioned set of the mCHP unit capacity, and with two working strategies. It is distinguished if the mCHP unit follows the load or it operates with a nominal output. The last factor is the system tariff schedule.

Table 1-3 Main variables for SOFC-based mCHP

Determinant	Value / Case
Size	1, 2, 3, 5, and 10 kW
Locations	Madison, Baltimore, Tampa Bay, and Phoenix
Operation mode	load follow, or nominal load
Rate schedule	residential schedule or optionally time residential schedule

2 APLICATION AND BACKGROUND OF MICRO-CHP

2.1 Fuel cell based micro-CHP background

Studies and work on the development of fuel cell based mCHP systems have been carried for over ten years. Scientific research, experiments and modeling focused both on SOFC and PEMFC systems. Oyarzabal et al.[19,20] developed an optimization model of proton exchange membrane fuel cell (PEMFC). The Local-Global Optimization method is applied, which is one of non-linear methods. Oyarzabal at al.[20] used the results to find the optimal fuel cell from the economic point of view. The authors found out that the cost of the fuel cell stack dominates the cost of the whole system. This indicates that there is a need for decreasing the cost of manufacture, platinum loading and membrane material. Oyarzabal et al.[19], basing on an economic model, obtained the optimal number of 50 residence for supply by a cogeneration system. An additional result of that optimization analysis was a conclusion that the system efficiency can reach 39% and the investment cost can be reduced to $2800/kW. This result indicates that a CHP unit based on the PEM fuel cell will be economical for a big apartment complex or single family dwelling when the production scale is increased.

Micro combined heat and power units based on PEM and SOFC were compared by Krist and Gleason [5]. The authors indicated that the main problem with sizing of those cogeneration units is the change in thermal requirements between winter and summer. The thermal to electricity ratio (TER) varies between 9 and 0.2 respectively between those seasons. The TER of mCHP units based on fuel cells is limited because electricity generation is restricted and combined with heat production. Another problem for the system sizing, according to Krist and Gleason research, is that peak demand can be five times higher than average loads of the mCHP unit. The authors point out the difference in thermal to electric ratio and efficiencies between internal combustion engines and fuel cells. TER of internal combustion (IC) engine is a lot higher, and those systems are suitable when the heat demand is larger. Efficiencies of IC engines are also higher for the full load operation, whereas fuel cells operate with high efficiency in a wider range. The authors show differences between fuel cells as well. The results of Krist and Gleason [21] study prove that fuel cells are attractive for home application. Moreover SOFCs have a lot of advantages over PEMFCs, such as higher efficiency, higher temperature of waste heat, no need for CO removal and humidification of the electrodes. The only advantage of PEM fuel cells was shorter starts-up time.

The solid oxide fuel cell applied as a micro combined heat and power unit was modeled by Lisbona et al.[21]. Their numerical model was made in Fortran and integrated into AspenPlus[TM]. The thermodynamic processes and electro-chemical reaction in the solid oxide fuel cell were included in the model. The model was used to predict performance of SOFC in different operation conditions, such as temperature, pre-reforming ratio, fuel utilization and gas utilization. The results obtained by Lisbona et al.[21] show that it is possible to achieve the electrical efficiency of the fuel cell of 45-51%. The heat and electrical efficiency have opposite trends but the system efficiency follows the thermal efficiency trends. For that reason it is important to optimize mCHP, SOFC based systems to reach higher thermal capacities.

Hawkes and Leach [22] in their work checked the possibility to use a mCHP unit based on SOFC for a dwelling, as a function of the system size. They considered the sensitivity of the system to different load demands, the price for electricity purchase and sale , the stack capital cost, the lifetime and electrical efficiency. The results show that the optimum of the stack size can be found for a large dwelling (1.25 kW$_e$)[22]. For a smaller dwelling, with a demand of around 1 kW, application of the mCHP unit would be economically reasonable if the investment cost decreased by 25% or energy prices were 25% higher. Studies made by Hawkes and Leach presented the optimal size of the stack of 1.25 kW for UK conditions. An interesting question is what capacity would be optimal for the USA and Polish markets actuality.

Continuing the research Hawkes et at.[23] developed a mCHP unit based on SOFC model, optimal to cover residential heating demand in the UK. The optimal heating profile for the CHP was developed basing on a variety of technological options for the heating of residential houses. The best system was composed of an under-floor heating system which was running during the whole winter. The results obtained were compared with a baseline case where heat is delivered from a gas boiler and electricity is supplied only from the grid. The micro combined heat and power unit, based on SOFC, provided a good economic result and CO_2 emission reduction.

The company TIAX[2] has been developing a grid independent fuel cell source. They have found out that the biggest problems are peak loads and efficiency drop when the unit operates at 10% of its nominal capacity. They claim that the fuel cell system has a lower efficiency than the average efficiency of the national electricity generation in the US, due to power supply to internal electronics. Although the fuel cell is less effective in generating electricity, it might be, however, a good base for mCHP unit. The TIAX company still did not offer the fuel cell based mCHP units.

Recently, research done by Braun[24] has shown the optimal micro-CHP system based on SOFC for residential applications with minimal life-cycle costs, and presented the sensitivity of the system to various economic parameters. Calculating the costs, Braun[24] took into account the system capital cost, maintenance costs and fuel costs. The optimal mCHP configuration is found when the fuel cell operates in the load following mode. The SOFC stack has an internal reformer of methane, and recycling of anode and cathode is applied. The system without cathode fuel reforming is also promising.

New research was performed for residential scale absorption chiller, which used heat from combined solar system and biomass furnace. The considered absorption chiller requires high temperature steam (150°)[38]. The chiller system is based on water-ammonia. Based on the results from Prasartkaew & Kumar [38] such absorption chiller could be considered with SOFC-based mCHP system. The absorption chiller would decrease electric load of a dwelling and increase the requirements for high quality thermal energy. The absorption chiller was not considered in this thesis because there are still few data regarding cost and exact performance of such device.

2.2   Assumption on heat and electricity demand

Thermal and electrical loads resulted from the household demands were prepared with the use of TRNSYS software. Characteristics of the buildings and data for chosen locations were prepared as an input to TRNSYS. The same building parameters were

assumed for all locations. The input data taken in to account are presented in tables 2-1, 2-2 and 2-3.

Table 2-1 Size of the considered dwelling.

Size	
Conditioned area	200 m^2
Conditioned volume	488 m^3
Wall area	150 m^2
Window area	34 m^2 (double paned)
Attic volume	176 m^3

Table 2-2 Construction materials.

Construction materials	
Outer walls	Framed with 0.6 cm wall board, 10.2 cm mineral wool insulation, plywood sheathing, and polyvinyl siding (U = 0.286 W/m^2-K)
Roof	Conventional roof-attic-ceiling combination with 10.2 cm mineral wool insulation and asphalt shingles (U = 0.203 W/m^2-K)
Floor	2.5 cm plywood with 12 cm of mineral wool insulation and crawl space (U = 0.260 W/m^2-K)
Windows	Double-paned with blinds (U = 2.7 W/m^2-K)

Table 2-3 Thermal conditions.

Comfort conditioning systems	
Cooling	Single-zone unitary vapor compression system with single thermostat
Heating	Natural gas-fueled, forced air convection
Hot water	Natural gas water heater
Conditioned space	0.75 air changes per hour

Demand for domestic hot water was assumed the same at all of the considered locations. The basic daily pattern is shown in the figure 2-1. The demand varies during the day between 0 and 2.7 kW$_t$. It has three peaks: the first of 2 kW$_t$ at 10am, the second of 1.35 kW$_t$ at 2pm. The biggest peak is at 8pm and reaches 2.7 kW$_t$. The daily average domestic hot water demand is 1.01 kW$_t$. It was also assumed in the model, that the domestic hot water requirements are a function of ambient temperature. Hot water demand was multiplied by a factor depending on temperature outside. This factor varies from 0.85 to 1.15 [37].
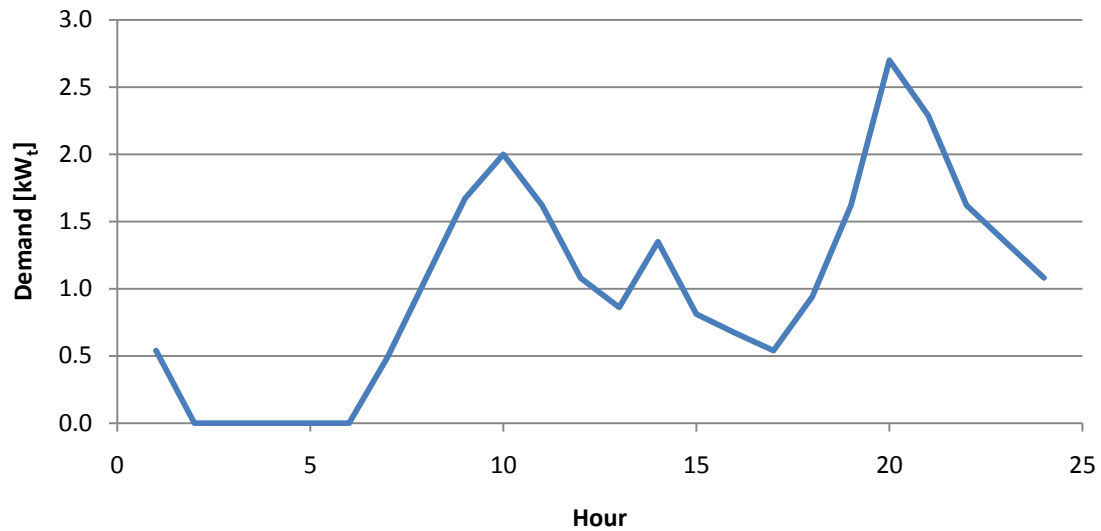
Figure 2-1 Assumed domestic hot water demand – a model case

The space heating is hourly based and it differs in all location. A characteristic of the maximum daily demand for space heating, during the year, was determined on the bais of the maximum demands at the particular hour. Those curves were applied as patterns for different locations. The highest curve is for Madison and the lowest for Phoenix. That pattern is recognized in space heating habits. In all location heat load slowly grows from midnight to seven a.m. when the morning peak starts. The peak in Madison reaches 16 kW and in Baltimore 11.7 kW. Peaks in Phoenix and Tampa Bay are lower and reach 8.1 kW at 8am and 6.5 kW at 7am respectively. After 8 am, the need for space heating falls down. In Phoenix and Tampa Bay during the heating season heating requirements drop to zero. After three o'clock heat load starts to rise in Madison and Baltimore. For all location the second peak is at 10 pm. Exact space heating loads profiles are shown in the figure 2-2. Data shown on this figure are maximum requirements at a given hour.
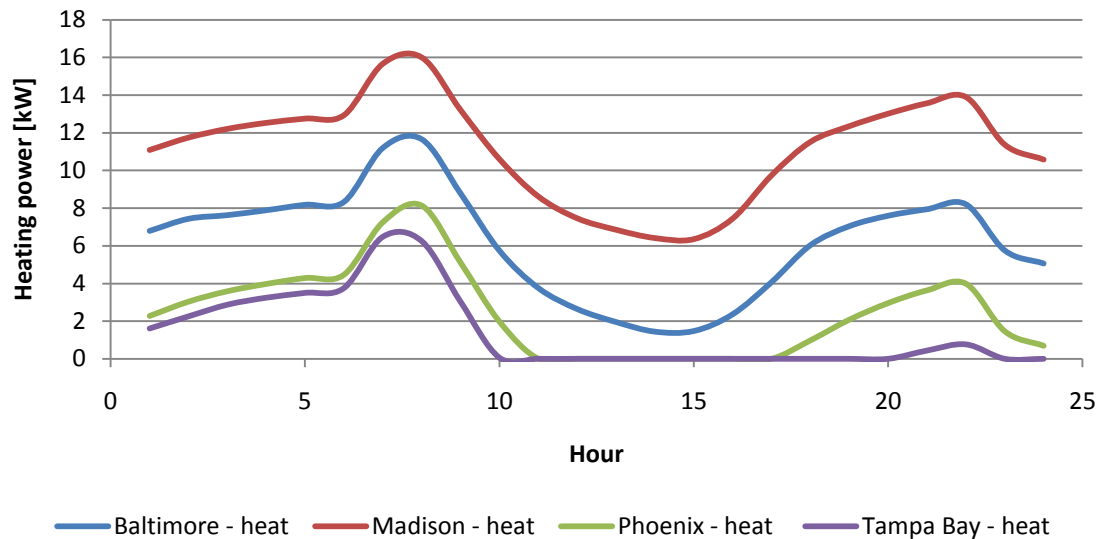
Figure 2-2 Maximum hour space heating requirements

The considered dwelling places also have cooling requirements. It has been assumed in the model that the cooling needs are covered with electrical chillers of a coefficient of performance equal to three. The demand for cooling stays only through summer and has one peak around 2 and 3 pm. The highest maximal daily average of cooling requirements is in Baltimore, and it is 7 kW per hour. The lowest is in Madison: 5.7 kW. Phoenix and Tampa Bay do not differ so much with an average of 6.25 kW and 6.5 kW respectively. In figure 2-3 maximal hourly cooling requirements are presented.
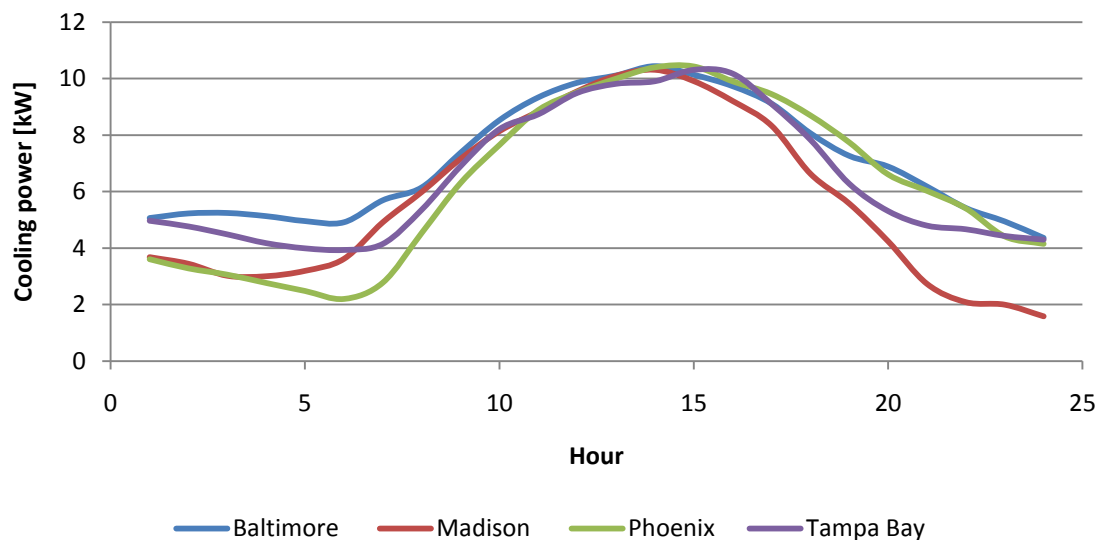
Figure 2-3 Maximum hour cooling requirements

In the model, the year was divided into a heating and cooling season. The periods' length depends on the climate. The heating season lasts for 90 days in warmer locations such as Phoenix and Tampa Bay, which is from December up to the end of February. In

the colder climate, such as in Baltimore, the heating season expands up to 181 days and starts in November. The longest heating season is in Madison where the climate is humid continental. It starts at the beginning of October and as in Baltimore stays up to end of April. It is similar to the climate in Poland, where the heating season varies from 200 up to 210 days, starts in mid October and last up to the end of April.

The basic demand for electricity is presented in figure 2-4. The basic electricity load means all electrical requirements exept the electricity used for cooling. For all of the considered locations the basic electrical demand was assumed to be the same. The assumption was made that the inhabitants' habits are similar. It was also assumed that the base electric load is the same every day throughout the whole year. Daily average electricity consumption for those basic needs is on a level of 0.9 kW. The basic electricity consumption gradually increases during the day. It reaches the peak at 5 pm and stays constant for three hours. The lowest basic electricity consumption is during the night at a level of 0.34 kW. As shown on the figure the main electricity consumption is due to cooling. During the peak of the cooling requirement the electrical load increases up to 3 kW. Figure 2-4 shows basic electric load and maximal electric increscent due to the electric cooling load. In the figure, the sum of the basic and electric cooling load was marked with suffix total.
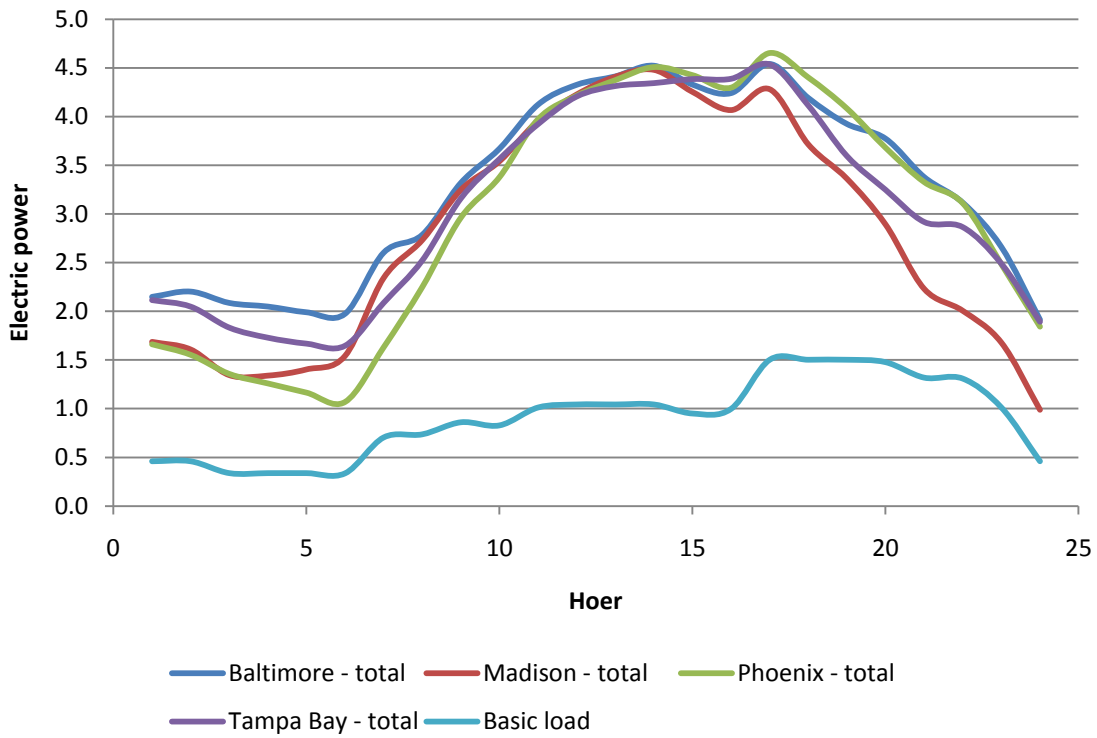
Figure 2-4 Basic electric load and total electricity consumption

The TERs for space heating and cooling are presented in the figure 2-5 and 2-6. The heating to electricity ratio was defined as a ratio of maximum hourly space heating requirements in kW to the average electricity demand at the hour, also in kW. It was calculated according to the equation,

$$TER_{heating} = \frac{E_{thermal}}{E_{electric}}. \qquad (2.1)$$

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Similarly to that, the cooling TER is a ratio of the maximum cooling requirement in kW to the average electric load at the same hour. It was calculated with the formula below.

$$TER_{cooling} = \frac{E_{cooling}}{E_{electric}} \qquad (2.2)$$
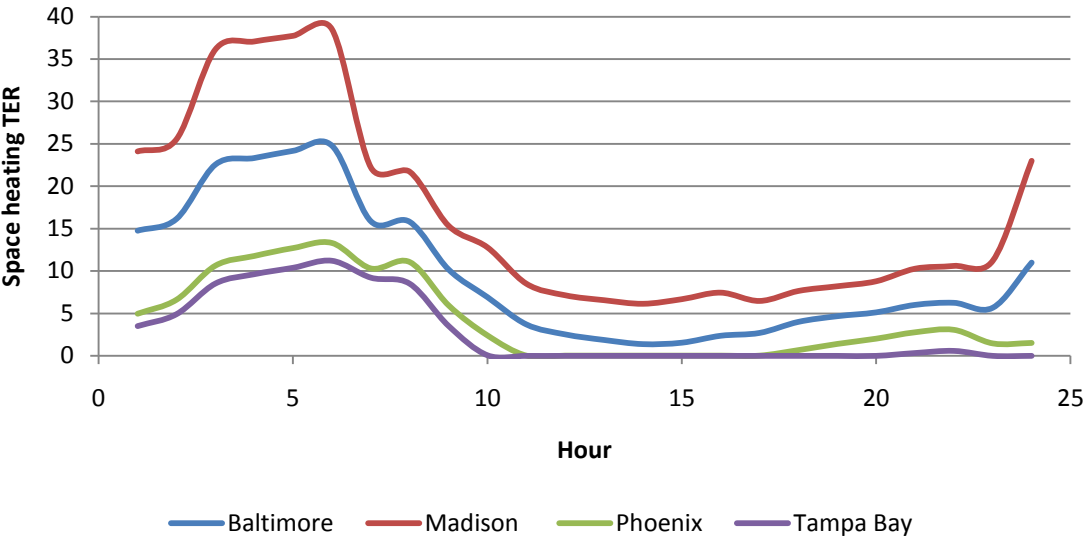
Figure 2-5 Heating thermal to electric ratio for maximal daily heating requirements

The TER for space heating varies between 6.1 and 38.5 in Madison and 0 and 11.2 in Tampa Bay. This fluctuation is even higher than given in Krist and Gleason work. This indicates that it can be very difficult to find the optimal parameters of the SOFC base micro combined heat and power system, if not impossible. The average values of TER are presented in table 2-4.
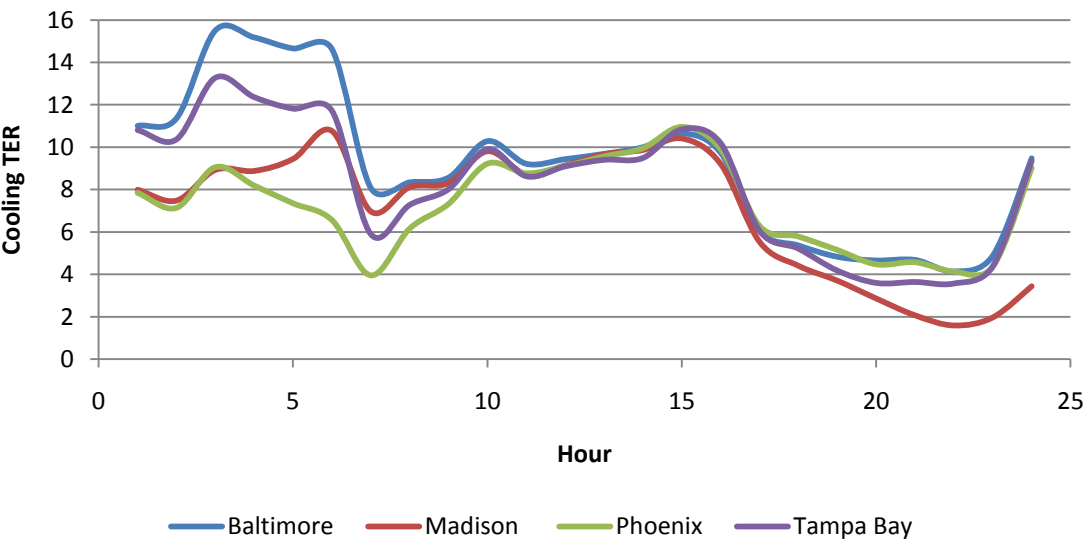
Figure 2-6 Cooling thermal to electric ratio based on maximal daily cooling requirements

Cooling thermal to electric ratio is constant throughout the day. The biggest variation is between 4.1 and 15.5 in Baltimore. The lowest value of the cooling TER is in Madison, and is equal to 1.6.

Average values of TER for space heating and cooling presented in the figures 2-5 and 2-6 are given in the table below. Yearly average values of TER of residential requirements are presented in table 2-4. The daily average is the average of maximum of heat and cooling demand at in each hour of the day.

Table 2-4 Daily and yearly average heating and cooling TER

	average of daily maximum		yearly average	
	Heating TER	Cooling TER	Heating TER	Cooling TER
Madison	16.67	7.06	2.70	0.65
Baltimore	9.73	9.18	1.63	0.97
Tampa Bay	2.93	8.29	0.54	1.60
Phoenix	4.27	7.28	0.61	1.53

The price of electricity delivered from the grid and the price of natural gas varies between the locations. Those depend on the provider of electricity and on the chosen tariff. The prices, which were assumed in the project are the actual prices for the residence sector. In Madison, the electricity price consists of a customer charge, which is paid per month, and an effective rate which is the price for every used kWh of energy. There is also a possibility that the effective rate will differ with time of day and season [25]. Seasons are divided into winter and summer, and they last for seven and five months respectively. According to Madison tariff, winter starts in October and lasts up to the beginning of May. The rest of the year is summer, when the peak hours are between 11 am and 8 pm only on week days. Peak hours during winter are between 7 am − 12 am and 5 pm − 8 pm, also only on week days. The prices for both types of the tariff in Madison are shown in Table 2-5.

Table 2-5 Electrical rates for Madison [25]

tariff	customer charge	effective rate			
	$/mo	$/kWh			
normal	5.7	0.120			
optional	5.7	SUMMER		WINTER	
		on-peak	off-peak	on-peak	off-peak
		0.219	0.072	0.219	0.072

The Baltimore system of tariffs is similar to the one in Madison. The hour tariff includes customer charge but the effective rate for electricity varies with the hour of a day. Moreover in Baltimore electricity prices are different during the summer (Jun 1 − Sep 30) and winter (Oct 1 − May 31) season. The prices during the summer are slightly higher than in the winter. The winter and summer seasons in Baltimore have on-peak, intermediate-peak (int − peak) and off-peak hours. The lengths of on-, intermediate-,

and off-peak are different during the summer and the winter. In the summer the on-peak lasts from 10 am to 8 pm and the intermediate-peak extends this period from 7 am to 11 pm. The winter peaks are divided in to two periods: the first from 7 am to 11 am, and the second from 5 pm up to 11 pm. The intermediate peak last from 11 am up to 5 pm. The rest of the day is the off-peak period. In the summer and in the winter, on- and intermediate peaks occur only during the week. Additionally to that, the customer has to pay for transmission and delivery services, and the payment depends on the chosen tariff and amount of used energy [26]. Prices from the Baltimore tariff are shown in table 2-6.

Table 2-6 Electrical rates for Baltimore [26]

customer charge	transmission	delivery service	summer			winter		
$/mo	$/kWh	$/kWh	$/kWh			$/kWh		
Normal tariff								
7.5	0.006	0.024	0.11333			0.09503		
Optional tariff								
7.5	0.005	0.020	peak	int - peak	off- peak	peak	int - peak	off- peak
			0.144	0.109	0.094	0.116	0.042	0.086

In Phoenix the customer can chose one of three different tariffs. According to the first one, customer has to pay a monthly charge and different effective rates during the summer (May – Oct.) and the winter (Nov. – Apr.). Moreover during the summer, the effective rate increases with higher electricity consumption, and during the winter it is constant. The second tariff prices change between the summer and winter season as well as between on- and off-peak periods. The seasons are the same as defined for the first tariff. The on-peaks last from 12 pm to 7 pm on weekdays and off-peak is for the rest of the time. The third tariff distinguishes the on-peak, the intermediate-peak (int-peak) and off-peak periods. The on-peak hours during summer are between 3 pm to 6 pm despite weekends. There are also no on-peak hours during the winter and the middle season. The intermediate-peak lasts three hours before on-peak period and an hour after it during the summer season. For the rest of the year, the intermediate-peak is between noon and seven in the evening. The off-peak period covers the rest of the time. In the third tariff, the summer starts at the beginning of June and lasts up to the end of August. The middle season is from the beginning of May up to the end of September as well as for the whole October. The winter season lasts for six month from November to April[27]. The prices for the all three tariffs from Phoenix are presented in table 2-7.

Table 2-7 Electrical rate for Phoenix [27]

tariff	basic charge		effectic rate		
			summer	middle	winter
	$/day		$/kWh		
first	0.29	first 400	0.097		0.094
		next 400	0.137		
		next 2200	0.163		
		rest	0.174		
second	0.56	on-peak	0.244		0.198
		off-peak	0.061		0.061
third	0.56	on-peak	0.494		
		int-peak	0.244	0.244	0.198
		off-peak	0.053	0.053	0.053

In Tampa Bay the customer has to pay separately for fuel, environment, capacity and energy conservation. The customer also has to pay a monthly customer charge and the effective rate. The fuel charge and the effective rate depend on the total energy consumption [28]. The prices are given in table 2-8.

Table 2-8 Electrical rate for Tampa Bay [28]

Requirements	fuel	energy conservation	capacity	environmental	customer charge	effective rate
kWh	$/kWh	$/kWh	$/kWh	$/kWh	$/mo	$/kWh
< 1000	0.042	0.0025	0.0054	0.0049	10.5	0.045
>1000	0.052					0.055

Excess of electricity from the fuel cell can be sold to the grid and lower energy cost are covered by the customer. In the United States energy market, the electricity sale and purchase can be measured with the use of the net metering. All of the U. S. electric companies are supposed to provide net metering on client's demand. This obligation is from Energy Policy Act of 2005[29]. Conditions and prices for electricity delivered to the grid vary with the utility. In the State of Wisconsin the electricity provider declares to pay for the total difference between energy supplied to the company grid and energy consumed. It is possible only if the total capacity of the customer's generators is 20 kW or less. Prices for electricity provided to the customer are different during the on-peak and the off-peak hours, and are $0.0941/kWh for the on-peak and $0.0372/kWh in the off-peak time[25]. The prices for which the utility is ready to buy electricity from the customer are 44% and 56% of the basic sale price during the on-peak and off-peak respectively. In Maryland, all district generators of electricity are required to meet safety and performance standards established by the National Electric Code, the Institute of Electrical and Electronics Engineers, and Underwriters Laboratories. Baltimore Gas and Electricity Company does not pay for extra electricity which the customer provides to the grid. The customer gets credits for extra electricity provided to the grid, which in next month bills can be used in next month bills[26]. In Florida, the electricity provider is ready to buy extra electricity for the avoided cost which is $0.0156/kWh. The Teco Tampa Electric, apart from safety requirements, do not have restrictions regarding onside power generators[28]. Similar to Wisconsin, in Arizona

extra electricity provided to the grid by the customer is bought for $0.0659/kWh and $0.0596/kWh during on-peak and off-peak periods respectively[27]. The net metering rules in Phoenix are related to fuel cells, which use renewable fuel or CHP units whose overall efficiency is above 42.5%. The overall efficiency is defined by ASP, Phoenix energy company, as the ratio of produced power and half of thermal energy to input in fuel[27]. The summary of conditions for the electricity delivery to the grid via the net metering was shown in table 2-9

Table 2-9 Net metering system

Location	Net metering price $/kWh		Comments
	On-peak	Off-peak	
Madison, Wi	0.0414	0.0208	Generator size 20kW or less
Baltimore, Md	0	0	Net electricity provided to grid is exchange for credits
Tampa Bay, Fl	0.0156	0.0156	Price of avoided cost, no additional requirements from system
Phoenix, Ar	0.0659	0.0596	Required efficiency of 42.5% and higher form CHP unit

The natural gas tariffs consist of the customer charge and the effective rate. The effective rate varies monthly and is set by the company. In Tampa Bay, the customer charge varies with the amount of used gas[25,26,30,31]. The prices of the customer charge and the effective rate for every month (for year 2010) are given in table 2-10 below.

Table 2-10 Natural Gas price for different location [25,26,30,31]

Annual consumption [therm]	madison	baltimore	tampa bay	phoenix
	customer charge			
	$/day	$/mo	$/mo	$/mo
0-99	0.2301	13	12	10.7
99-249			15	
249-1999			20	
month	effective rate			
	$/therm			
jan	0.984	0.726	0.267	1.313
feb	0.971	0.659	0.272	1.313
mar	0.994	0.662	0.272	1.279
apr	0.893	0.558	0.272	1.257
may	0.826	0.608	0.246	1.230
jun	0.738	0.591	0.246	1.222
jul	0.836	0.672	0.219	1.214
aug	0.808	0.659	0.192	1.208
sep	0.728	0.561	0.192	1.204
oct	0.741	0.570	0.192	1.204
nov	0.864	0.562	0.192	1.200
dec	0.911	0.637	0.219	1.196

3 MODELING AND SIMULATION

3.1 Model requirements

The SOFC-based mCHP system is simulation, a steady-state thermodynamic model, based on deterministic parameters. It can be applied to four different locations, and one of the eight various tariffs for electricity sale to the customer, and for determined conditions for the electricity delivered to the grid. The computations can be done for any of the system capacities: 1, 2, 3, 5 and 10 kW. That scope of unit size is based on previous work on mCHP systems, and the assumption that the micro combined heat and power system capacity does not exceed 10 kW. The model also allows to distinguish an operation strategy.

One of the possible operation strategies is the load following (LF) mode. In such an operation mode the fuel cell is generating electricity trying to copy the pattern of the electricity demand. It is assumed that the fuel cell is able to deliver a 0.01 kW over its capacity. For a demand smaller than the turn down ratio of the considered fuel cell, the power demand is fulfilled from the grid.

An alternative operation strategy, called the nominal output (NO) mode, is when the unit operates with a steady output, equal to the nominal capacity of the fuel cell, regardless of the current demand.

The model of the SOFC-base mCHP unit with heat recovery and storage is based on a set of equations describing the system. The solution of those equations gives values of the variables for each considered hour of operation.

System operation is considered in one hour steps. The model identifies working point for each hour of the year, and integrates the results for the whole year estimating the yearly fuel consumption, heat and electricity production, fuel costs, electricity costs and a revenue from the excess electricity sale.

Electric load as well as heat demand are used on hourly basis in the model, and the computations done with the use of the model are based on the hourly average values of those demands. It is also assumed that there is no cooling demand during the heating season, and no heating requirements during the cooling season. The temporary demand can differ from the average and due to that, the obtained results are only an approximation of a real mCHP system operation.

The model approach is illustrated in figure 3-1. It presents the methodology of data collecting for the system optimization and provides conclusion on the economy of SOFC based micro-CHPs.
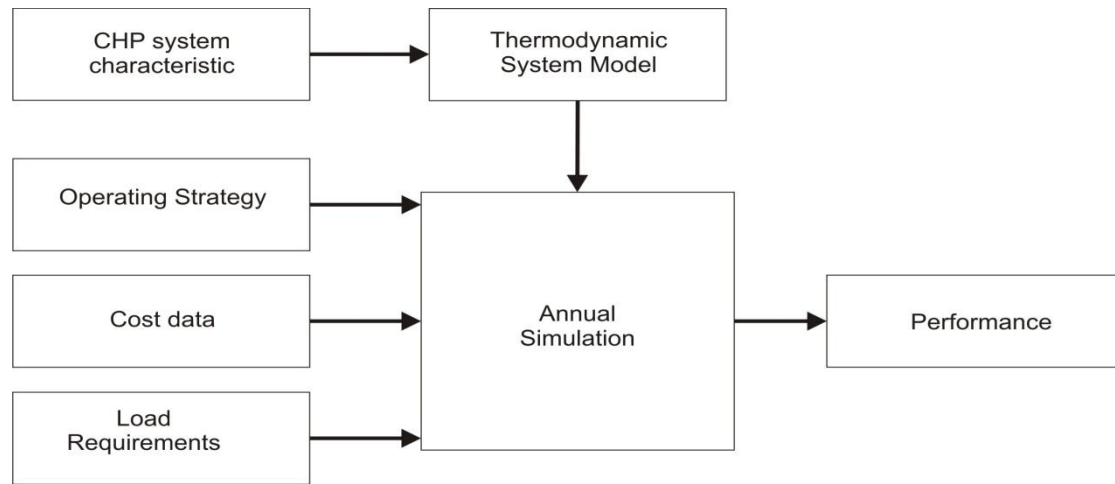
Figure 3-1 Model outline

The annual simulation inputs will include the thermodynamic model of SOFC, operating strategy, costs and power demands. All this processed data will give results concerning the performance of a SOFC based micro-CHP system for the assumed load requirements and cost of the components. The same model will be used to analyze the sensitivity of the system.

The best performance parameters of the system will be obtained by comparing results of the simulations. As mentioned above the main change of the data for simulation analyses will be the change of the climatic data, characteristic for the chosen locations. Apart of that, a variety of tariffs in the locations will have an impact on the optimal solution preferred for the site.

3.2   SOFC

The solid oxide fuel cell (SOFC) stack is typically operated at the temperature of 800°C and it generates direct current (DC). The DC is next converted to alternating current (AC) in the inverter. The inverter efficiency reaches a level of 92%[24]. The mCHP unit with a SOFC is composed of a fuel cell stack, heat exchangers, funs and water/fuel pumps. The considered unit operates with anode recycling. The scheme of the system is presented in figure 3-2[32]. The fuel compressor pumps fuel from a tank through the desulfurizer and the heat exchanger to the stack. The sulfur content (H_2S) in the fuel is reduced to less than 0.1ppm at the desulfurizer, and it does not affect the cell voltage[33]. Next, a fresh fuel stream is mixed with the recycled unburned fuel taken from the outlet of the fuel cell. Anode recycling results in an increase of electrical efficiency and overall efficiency of the mCHP unit by over 10 percentage points [24]. Before fuel enters the fuel cell it is preheated at the pre-reformer with a heat of the exhaust gases. The fuel is preheated up to about 50 degrees below the nominal operation temperature of the fuel cell, of 800°C. The desulfurized and preheated fuel enters the fuel cell where it undergoes internal reforming, and then an electrochemical reaction during which chemical energy is converted into electricity. Air is used as an oxygen carrier. The air must be also preheated before entering the fuel cell. It enters the fuel cell at a similar temperature to the fuel inlet temperature. The air is filtered and pressurized before the pre-heater. The fuel which was not consumed at the fuel cell is partially recycled and mixed with a fresh stream of natural gas, and partially it is burned in a

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combustor. Heat of the exhaust gasses is utilized for fuel and air preheating and for supplying the building heating system.
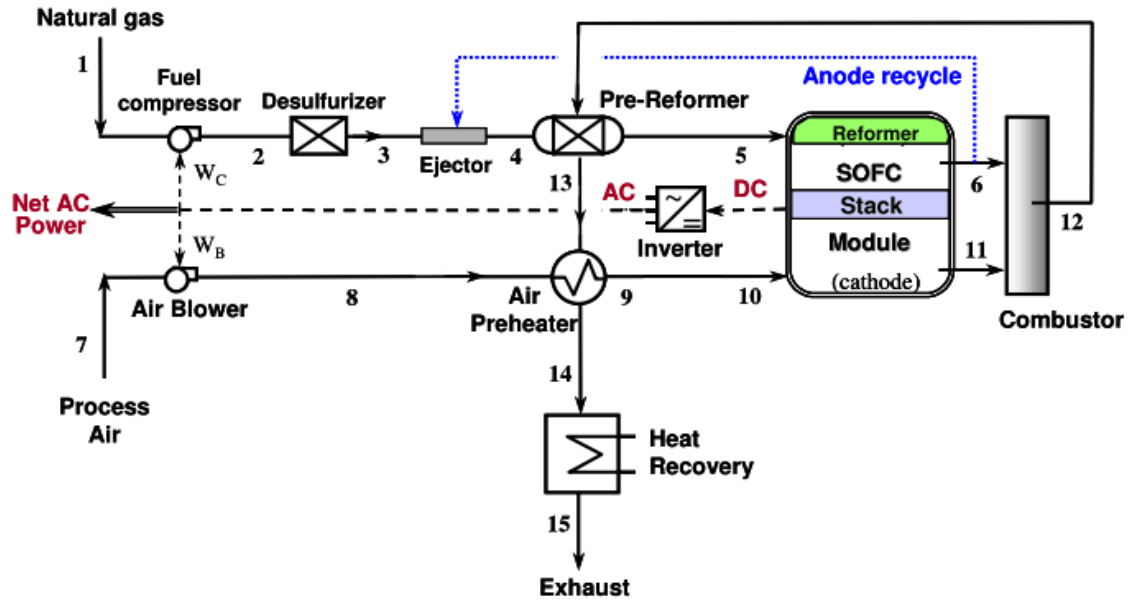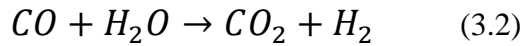

Figure 3-2 Methane fueled SOFC CHP system[32].

Natural gas supplying the fuel cell undergoes a direct internal reforming process. In this process methane and steam mixture converts into hydrogen and carbon dioxide and carbon monoxide, according to equations 3.1 and 3.2 [21].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (3.1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (3.2)$$
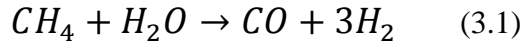
Reaction 3.1 and 3.2 are the main reactions which occur in the fuel reformer. The ratio of each compound depends on the equilibrium of all reactions which appear. The main advantages of the internal reforming processes is an increase in efficiency due to lower parasitic load and higher heating transfer[17]. The disadvantage of that process is the possibility of carbon formation on the surface of the anode.

Electricity generated in the solid oxide fuel cell according to reactions 3.3, 3.4 and 3.5 is partially used for the parasitic load [18].

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (3.3)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad (3.4)$$

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad (3.5)$$
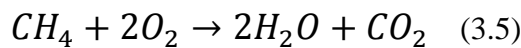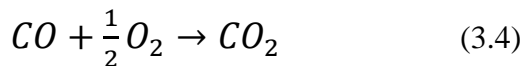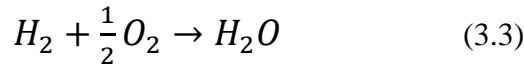
Although all those three reactions are possible, the dominating one is the reaction 3.3.

The utilized fuel fraction is defined by equation 3.6, and the air excess is identified by equation 3.7. The fuel utilization in a commercial SOFC is at range of 75-85%[17]. The air excess is high and around 7 due to the fact that the air is also used for the fuel cell cooling. On average, the air temperature increases by 100°C[17]. The disadvantage of

such a cooling system is that high air excess causes high load requirements of the air blower, and an increased parasitic load.

$$U_f = \frac{moles\ of\ fuel\ consumed}{moles\ of\ fuel\ supplied} \quad (3.6)$$

$$U_f = \frac{moles\ of\ oxygen\ supplied\ with\ air}{moles\ of\ oxigen\ needed\ for\ stoichiometry} \quad (3.7)$$

The fuel cell performance is typically presented with the function of current density. The value of this function is the fuel cell voltage and it is shown by equation 3.8 from [33].

$$E = E^0 - \frac{RT}{nF}\ln\left(\frac{i}{i_0}\right) - iR - \frac{RT}{nF}\ln\left(1 - \frac{i}{i_L}\right) \quad (3.8)$$

At the equation 3.8 E^0 is the reversible cell voltage, T is the temperature of the cell, F is the Faraday constant, i is the current density, i_L is the limiting current density and R is the total cell resistance. The first component of the equation is the reversible electrochemical cell voltage corrected through the temperature, pressure and concentration changes. The second component represents the activation losses in the fuel cell. Activation losses are not linear and have the biggest effect for small current densities. Ohmic losses are represented by the third element of equation 3.8. Ohmic losses are linear for all rang of fuel cell operation. For the highest current densities, voltage depends mainly on linear ohimc losses and non-linear concentration losses. Concentration losses are demonstrated in the last part of equation 3.8. Typically, SOFCs are dominated by ohmic and concentration losses[18]. The cell voltage as a function of current density is shown in figure 3-3[17].
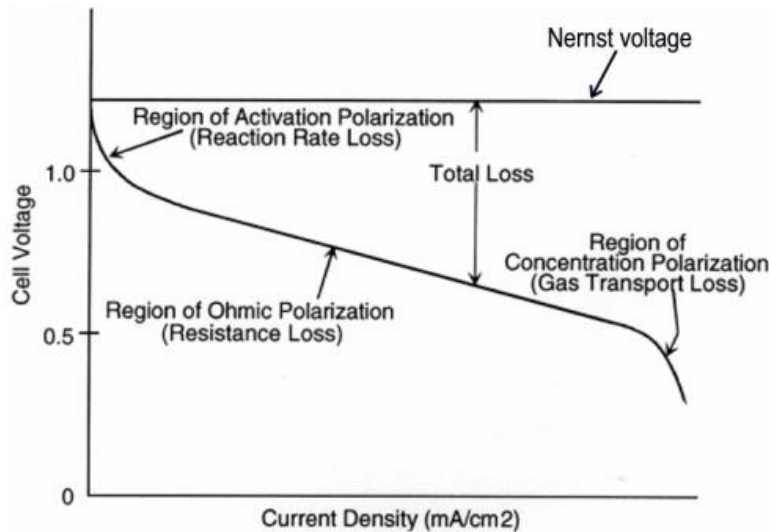
Figure 3-3 Cell voltage performance as a function of current density[17].

Due to direct conversion of chemical energy into electric energy, fuel cells are expected to have a higher efficiency than heat engines. The reversible HHV efficiency of the fuel cell is significantly higher if compared to the reversible efficiency of the heat engine for low temperature. At a higher temperature the reversible efficiency of the heat engine increases unlike the reversible efficiency of the fuel cell, and the difference is a lot lower[18]. The real fuel cell efficiency is given in equation 3.9 and it is multiplication

of thermal, voltage and fuel efficiencies[18]. The fuel efficiency is the ratio of the used fuel to the fuel provided to the fuel cell.

$$\varepsilon_{real} = \varepsilon_{thermo} * \varepsilon_{voltage} * \varepsilon_{fuel} = \frac{\Delta\hat{g}}{\Delta\hat{h}} * \frac{V}{E} * \frac{i/nF}{v_{fuel}} \quad (3.9)$$

Efficiency of the fuel cell depends on many factors. The thermal efficiency is affected by the operation temperature with which it decreases. The fuel efficiency is strictly connected with the fuel utilization factor. The voltage efficiency decreases with the current density. It is also possible to defined fuel cell efficiency as a ratio of the produced energy to the energy provided in the fuel. That efficiency will be used in this work and it is presented in equation 3.10.Moreover, the electrical efficiency of the system and the overall CHP system efficiency can be defined by equations 3.11 and 3.12.

$$\eta_{SOFC} = \frac{P_{DC}}{\dot{n}_{fuel,in} * HHV_{fuel}} \quad (3.10)$$

$$\eta_{sys} = \frac{P_{AC}}{\dot{n}_{fuel,in} * HHV_{fuel}} \quad (3.11)$$

$$\eta_{CHP} = \frac{P_{DC} + Q_{rec}}{\dot{n}_{fuel,in} * HHV_{fuel}} \quad (3.12)$$

Those efficiencies are related to the electric power generated in the fuel cell (P_{DC}), the net electric power supplied to the house of to the grid (P_{AC}) and the total heat and electric power of the CHP unit ($P_{AC} + Q_{rec}$). The efficiencies are calculated on the basis of the higher heating value of the fuel.

3.3   Heat recovery system

The heat recovery system for both space and domestic hot water heating consists of heat exchangers, a heat accumulator, and an auxiliary boiler. The available heat of the exhaust gases is recovered through gas-gas heat exchanger to the air. The temperature of the air is increased from 20°C to 35°C. The mass of air which is heated up depends on the current heat demand at the considered hour. Fuel cell exhaust gases are directed from the space heating heat exchanger to the gas-water heat exchanger where the rest of the available heat is recovered for domestic hot water requirements. The second heat exchanger works in a closed system with a heat accumulator. The maximum temperature of water in the heat accumulator is set at 60°C to prevent silica, calcium chloride and magnesium salt precipitation, which dramatically increases above this temperature [34]. The exhaust gases should not be cooled down below 60°C to avoid condensation of vapour. If the temperature of fuel cell gasses leaving the first heat exchanger is not higher than 60°C the fuel cell gasses are removed through the bypass and are not directed into the second heat exchanger. Figure 3-4 present the heat recovery system.
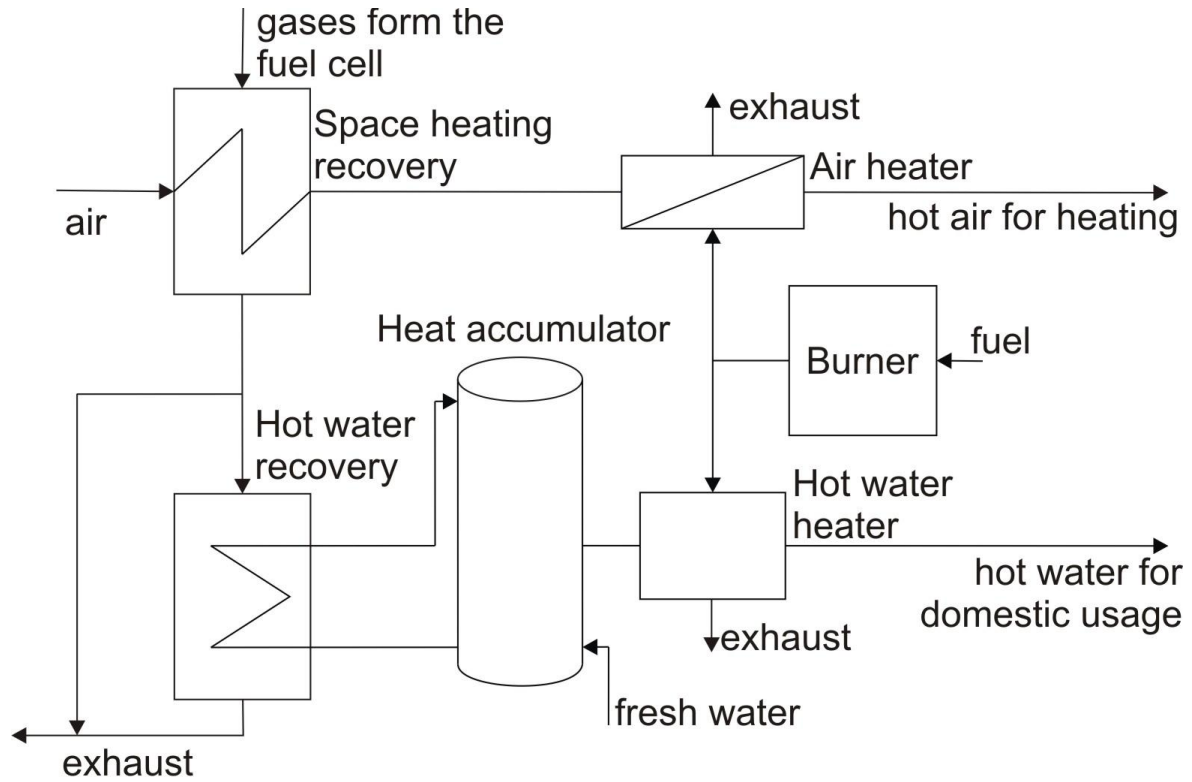
Figure 3-4 Heat recovery system

3.4 Economic

An economic analysis of the system helps us to find what can be done to make technology more likely to develop. In this thesis, the combined cost of a mCHP system with SOFC resulting from investment costs, fuel costs, electricity prices and cost of operations and maintenance (O&M) of the system. For the nominal output operation mode also net metering plans were included to calculate possible revenues.

The investment costs of the SOFC based mCHP unit, and differences in costs before and after the investment are taken into account. Before installation of the unit the customer covers the costs of gas used for space and domestic water heating, and costs of electricity consumed for basic needs (lighting, cooking, etc.) and for space cooling. When the SOFC mCHP system is applied the costs of electricity can be reduced, costs of gas slightly increase, and some additional O&M costs occur.

The total difference between earlier and new costs is considered as a yearly cash flow. Cash flows can be negative or positive. The equation for cash flow in every year is as follows

$$Cash\ Flow = C_{gas} + C_{electricity} - C_{gas\ new} - C_{electricity\ new} - O\&M. \qquad (3.13)$$

In this thesis it is assumed that yearly cash flows are constant throughout the years. All prices and costs are converted to 2010 dollars.

3.5   Input data for the system simulation

The general specification and requirements regarding the considered SOFC-based micro combined heat and power system are presented in table 3-1.

Table 3-1 Set system values

Parameter	Value
COP of air conditioning	3
Heating thermostat setting – required room temperature[°C]	20
Cooling thermostat – required room temperature [°C]	24
Domestic hot water delivery temperature [°C]	60
Temperature of fresh water [°C]	10
Maximum temperature of the water accumulated at the tank [°C]	60
Tank volume [liters]	200
Minimal outlet temperature of the exhaust gases[°C]	60
Efficiency of the auxiliary boiler	90%
Nominal capacity to the turn down ratio	5:1

The SOFC based mCHP system investment cost changes with its capacity. The number of cells increases with the size of the fuel cell. Those data are included in the table below.

Table 3-2 SOFC base mCHP capital cost and cells nr in stack [24]

System size [kW]	mCHP price[$/kW$_e$]	Number of cells
1	2040	49
2	1530	97
3	1345	138
5	1180	245
10	1040	388

The costs of operation and maintenance were taken after Braun [24] previous work, and were estimate at a level of 0.02 $/kWh [24]. The load inputs as well as utility prices are described in the chapter 2.2. The demand for domestic hot water is presented in figure 2-1. Patterns of thermal heat loads as well as cooling demands are shown in figures 2-2 and 2-3. Daily electric demand was presented last in the figure 2-4.

Precise description of the costs of gas, electricity as well as net metering tariff is also in chapter 2.2. Its summary is presented in tables from 2-5 to 2-10.

The counted grid emissions were based on average CO_2 emissivity of a electricity mix in considered state. The grid emissivity is presented in the table 3-3.

Table 3-3 CO_2 grid emissivity in different location [39]

Location	Madison	Baltimore	Tampa Bay	Phoenix
CO_2 emission rate [lbs/kWh]	1.713	1.293	1.348	1.219

4 SIMULATION RESULTS

4.1 Technical results

4.1.1 Electric capacity factor

At least two capacity factors can be defined and calculated for the SOFC-based mCHP system. The first is the electric capacity factor (CF) for house, what is the ratio of total electricity generated at the fuel cell to total electricity consumed in the dwelling. The calculation formula is presented below.

$$CF_{house} = \frac{E_{total}}{E_{demand\ total}} \quad (4.1)$$

The electric CF for house is, next to thermal to electric ratio, the best way to adjust the right size and operation strategy of the fuel cell to the dwelling requirements.

Another CF is called electric capacity factor for the SOFC, and it is the ratio of total electricity generated in the system to the possible generation, as if the system operated permanently with the nominal capacity. This factor depends on the operation strategy and is a measure of use of the installed capacity of the SOFC system. The formula for the SOFC capacity ratio is

$$CF_{SOFC} = \frac{E_{total}}{P_{max\ SOFC} * 8760}. \quad (4.2)$$

The factors CF$_{house}$, and CF$_{SOFC}$, defined above, calculated for the SOFC based mCHP system which operates following the load, and for the 4 locations under consideration, are presented in the figure below.

(a)   (b)
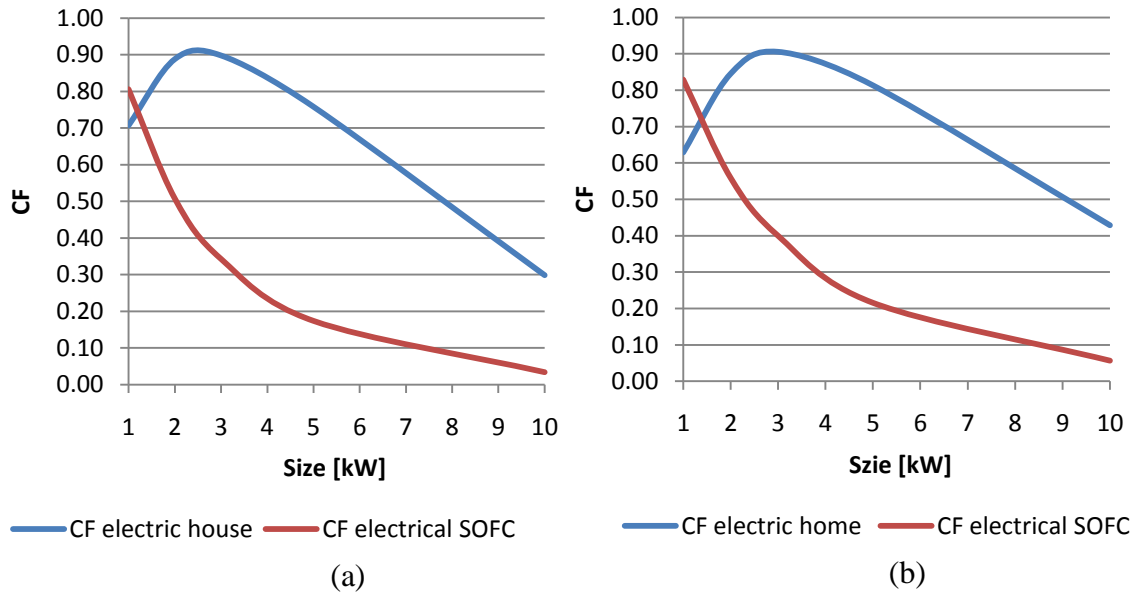
Figure 4-1 Capacity factors for the system which operates following the load: (a) Madison, (b) Baltimore, (c) Tampa Bay, (d) Phoenix.

The CF_{house} for a system which operates following the load, calculated for Madison, has the maximum value for the mCHP capacity between 2 and 3 kW. An advantage of the 2 kW system above one of 3 kW capacity is that it has CF_{SOFC} over 15 percentage points higher. Both factors drop rapidly with a further increase in the system size. .

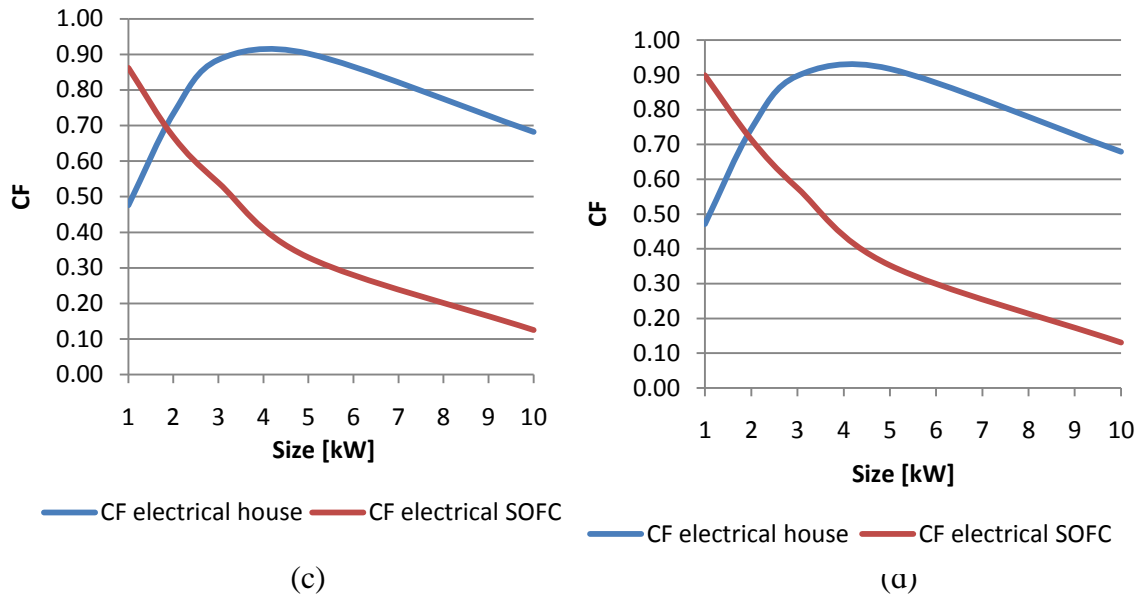In the case of Baltimore, the maximum of the CF_{hosue} has been found for a 3 kW system operated at the load following strategy. It is 6% higher than for a 2 kW unit and 10 percentage points higher than for a 5 kW system. The CF_{SOFC} decreases with the unit size. It drops by 16% if we compare 2 kW and 3 kW systems and by 18% between 3 kW to 5 kW units.

With Tampa Bay loads characteristics, the maximum of the CF_{hosue} is reached for a system of about 4 kW capacity, and it is equal to 92%. The 3 kW system is close to this and with CF_{hosue} smaller by 2%. Although the CF of SOFC drops from 58% for a 3 kW system to 35% for a 5 kW one.

The maximum CF_{hosue} for a dwelling in Phoenix is near to the CF_{house} for the 5 kW unit size and it is equal to 90%. Close to it is the 3 kW system which has a capacity factor of 89%. Similarly to other locations, the capacity factor of the solid oxide fuel cell decreases with the system size and the CF_{SOFC} is 86%, for a 1 kW system, 54% for 3 kW, 33% for 5 kW units.

The capacity factor of house (CF_{hosue}) curve is shaped by many mutually related determinants, such as the current hourly demand, maximal and minimal electricity generation at the fuel cell. The numerator in 4.2 equations is constant for the chosen dwelling regardless of the possible electricity production. The rise of CF_{house} for smaller units results from an increase in generation when the unit capacity rises. With a growth of the mCHP system size, the turn down output grows as well. For bigger capacity units load requirements are often smaller than the minimum possible output of the mCHP system, the unit must be off for longer periods, and it results in CF_{house} reduction.

The SOFC capacity ratio CF_{SOFC} decreases even for smaller units due to a faster increase of a generation abilities than the growth of potential production. For slightly bigger capacities, when also the CF_{house} decreases, the possible production is more and more limited with a growth of the system size.

Comparison of electrical capacity ratio for house and SOFC for all four locations is presented in Figures 4.2 and 4.3. This confrontation of CF for the systems applied in different sites shows which of them fits better for SOFC mCHP use.
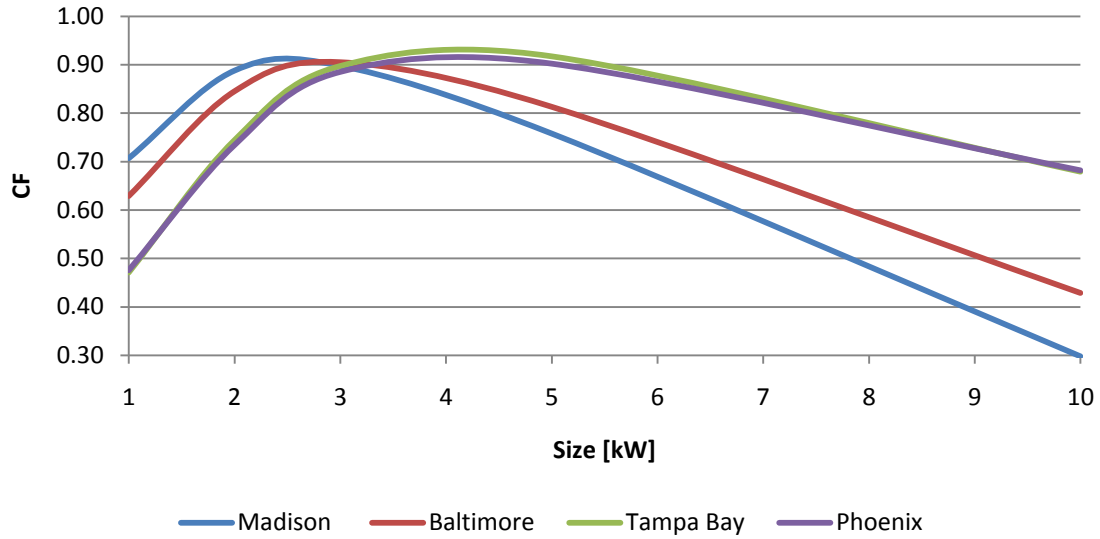
Figure 4-2 Comparison of capacity factor of house

It is observed that the optimal size of a SOFC based mCHP increases from 2 kW unit in Madison to almost 5 kW in Tampa Bay and Phoenix. The optimal size of the system for Baltimore is between them, with a maximum at 3 kW. It is also indicated that the capacity ratio for bigger systems is higher in warmer locations. It is opposite for systems smaller than the optimal size.

The increase in optimal fuel cell size is caused by higher annual electricity consumption. Electricity CF for house is one of many indicators which show the optimum. However, there are many others factors which cannot be forgotten and also have to be included in finding the optimum of the whole micro combined heat and power system for residential application.
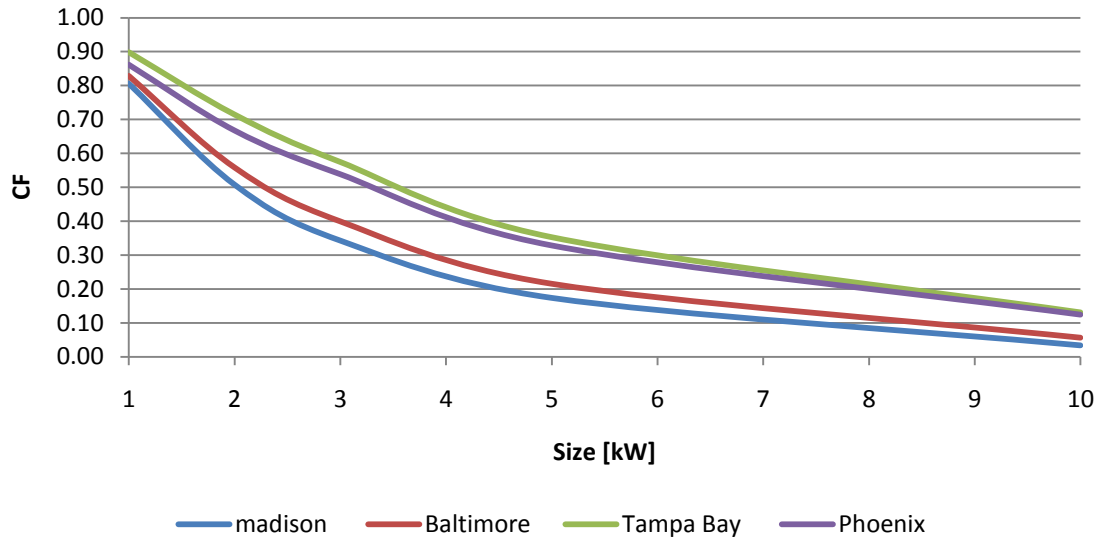
Figure 4-3 Comparison of capacity factor of SOFC

The comparison of the electric capacity factor for SOFC (CF_{SOFC}) for the four different locations shows that the highest CF_{SOFC} in in the system in Tampa Bay. Similarly to the application of the mCHP in Tampa Bay, the CF_{SOFC} for Phoenix also has high values. The lowest are the coefficients evaluated for the system applied in Madison. The maximal value of CF_{SOFC} in the considered cases is 92% found for a 1 kW SOFC based mCHP unit proposed for operation in Tampa Bay. The capacity factor for SOFC drops with the unit size.

Capacity factors vary between the locations because of the differences in hourly demands. Bigger SOFCs would not operate with full capacity or would be off due to the high turn down ratio. The higher curve in Figure 4-3 indicates that the device would operate longer closer to its capacity. Longer operation is possible with shorter periods when the load is below the minimal working point.

The optimum of SOFC-based mCHP based on the electrical capacity factor was shown in the table 4-1.

Table 4-1 Optimum of SOFC-based mCHP based on electric capacity factor

Location	Optimum			
	Size [kW]	CF_{House}	Size [kW]	CF_{SOFC}
Madison	2	90%	1	81
Baltimore	3	91%	1	83
Tampa Bay	5	92%	1	90
Phoenix	5	90%	1	86

4.1.2 Thermal capacity ratio

The thermal capacity factor as well as the electric CF can be defined both in relation to the demand as the CF for house, and in relation to the supply abilities as the CF for the SOFC system. The thermal capacity factor for house $CF_{thermal\ house}$ is the ratio of heat

recovered from the mCHP for space heating and domestic water heating, to the total heat demand for those purposes at the dwelling. This ratio presents the system ability to cover heat requirements at a household. It can be expressed by the equation

$$CF_{thermal\ house} = \frac{Q_{rec\ DHW} + Q_{rec\ SH}}{Q_{DHW} + Q_{SH}}, \qquad (4.3)$$

where index *rec* means 'recovered', DHW is relates to domestic hot water and SH is an abbreviation of space heating. The heat capacity ratio of SOFC $CF_{thermal\ SOFC}$ is the ratio of the total heat recovered to the total maximum possible heat recovery from the mCHP system. It is defined by the formula below.

$$CF_{thermal\ SOFC} = \frac{Q_{rec\ DHW} + Q_{rec\ SH}}{Q_{rec\ MAX}} \qquad (4.4)$$

The index MAX stands for the total maximal heat recovery from the SOFC mCHP system. The thermal CF for SOFC illustrates how well heat is recovered from the solid oxide fuel cell based micro combined heat and power system. Both indicators can be calculated for alternative operation modes: when the systems follows the load and when it work with the nominal output. The results for all location are presented below.

(a) (b)
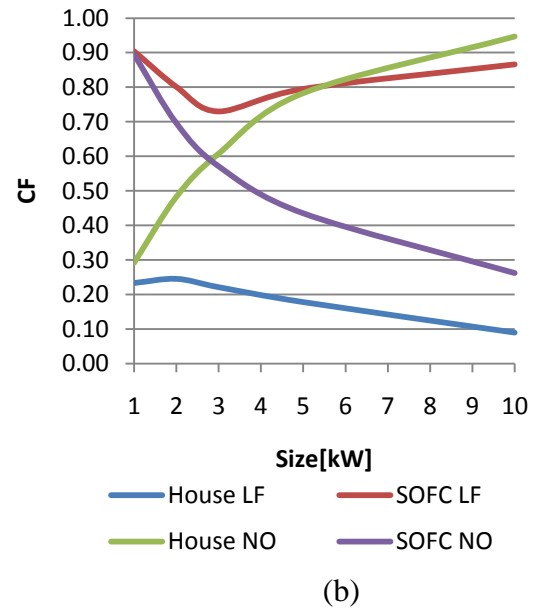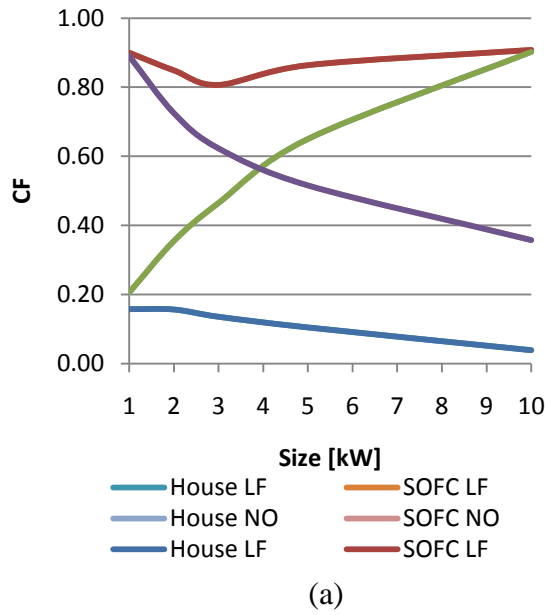
Figure 4-4 Thermal capacity factor for an operation in load follow and nominal output operation mode in (a) Madison, (b) Baltimore, (c) Tampa Bay, and (d) Phoenix.

The results obtained for Madison show that when the system operates with a steady nominal output the $CF_{thermal\ house}$ is much better than if it operates following the demand. The maximum house thermal capacity factor for the load following mode is for the 1 kW and 2 kW systems, and equals to 16%, whereas in the nominal output scenario it varies between 21% and 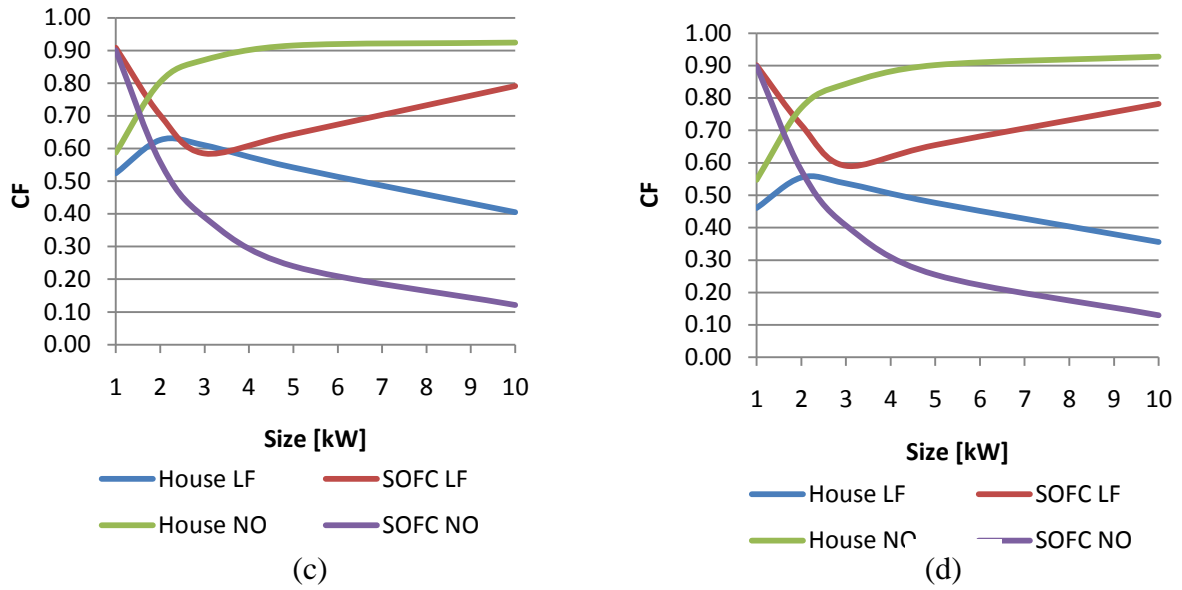90%, and reaches maximum for the 10 kW system size. The thermal capacity factor $CF_{thermal\ SOFC}$ values are higher for the load following operation mode than for the nominal output. The minimum of the thermal $CF_{thermal\ SOFC}$ in the load following mode is for the 3 kW system and it is equal to 81%. The maximum is for the 10 kW fuel cell and it matches 91%. Th high value of the $CF_{thermal\ SOFC}$ has also been calculated for the 1 kW unit, when it attains a level of 90%. The $CF_{thermal\ SOFC}$ decreases with the system size if it operates in the 'nominal output' mode, from 89% for the 1 kW unit to 36%. for the 10 kW unit.

Thermal capacity factors evaluated for Baltimore have similar patterns as in the case of Madison. The $CF_{thermal\ house}$ has the maximum equal to 25% for the 2 kW system if it operates following the demand (LF mode) and the maximum equal to 95% for the 10 kW unit if the mCHP operates with a steady nominal output. The thermal CF for house generally decreases with the system size in the load following operation , and it constantly increases for the operation with the nominal output. The $CF_{thermal\ SOFC}$ decreases for units of size between 1 kW and 3 kW if operated in the LF mode, and increases for bigger capacities of the SOFC. The highest value of the $CF_{thermal\ SOFC}$ in the nominal output operation is for the system of 1 kW capacity and equals to 90%. It decreases with the size of the fuel cell.

The house capacity factor of the system applied in Tampa Bay varies between 41% and 63% if operated in the load following mode, where the maximum of the $CF_{thermal\ house}$ is for the 2 kW system. In the same operation mode, the minimum of the $CF_{thermal\ SOFC}$ is the 3 kW capacity unit and it is equal to 59%. The $CF_{thermal\ house}$ reaches the maximum value of 70%. The mCHP system operating with nominal output has a maximal values of $CF_{thermal\ house}$ of about 92% if the system capacity is between 10 and 5 kW and it

drops to 87% for the 3 kW system. For the same operation mode the $CF_{thermal\ SOFC}$ decreases from 39% through 24% and to 12% for 3, 5 and 10 kW systems respectively. The maximum of the capacity factor for the SOFC is 90% for the 1 kW unit.

The thermal capacity factor for a dwelling in Phoenix, $CF_{thermal\ house}$, for the load following operation reaches 56% for the 2 kW unit. Similar to the case of Tampa Bay, in the same operation mode, the SOFC thermal capacity factor has a minimum of 59% for units of 3 kW and 2 kW capacities. The $CF_{thermal\ house}$ for the nominal output operation increases rapidly with the size of the system up to 3 kW capacity and after that it the decreases. The maximum of the $CF_{thermal\ house}$ in the nominal output mode is for the 10 kW system size, and it is equal to 93%. On the other hand, SOFC thermal CF rapidly decreases with size. The maximum of it attains a value of 90% for the 1 kW unit. The decrease of the SOFC thermal CF between the 3 kW system and the 5 kW one is 15 percentage points and between the 5 kW unit and the 10 kW unit it is 13 percentage points. The SOFC thermal CF for the 10 kW mCHP system is 13%. The best system size based on thermal capacity factor were shown in the table 4-2.

Table 4-2 The system optimum based on thermal capacity factor

Location	Load following		Nominal output	
	CF_{house} [kW]	CF_{SOFC} [kW]	CF_{house} [kW]	CF_{SOFC} [kW]
Madison	1&2 (16%)	1 (81%)	10 (90%)	1 (89%)
Baltimore	2 (25%)	1 (90%)	10 (95%)	1 (90%)
Tampa Bay	2 (63%)	1 (91%)	5 & 10 (92%)	1 (90%)
Phoenix	2 (56%)	1 (81%)	10 (93%)	1 (90%)

Thermal capacity factor curves for the load following operation mode are very interesting. Their maximums are moved in comparison to electric capacity factors. For Madison and Baltimore this change is hard to notice, but for Tampa Bay and Phoenix the difference is significant. In this case the decrease for the load following operation is caused by the turn down ratio, but also by seasonality of heat and electricity demand. During winter, heating requirements are high but the demand for electricity is limited. On the other hand in summer, due to the demand for cooling, electricity consumption is high. This situation generates big potential for electricity generation in warmer places, moving electric CF peak towards bigger systems. During winter, however, there is no need for bigger supply and the turn down ratio shutdowns the fuel cell.

Thermal capacity factors for the nominal output operation are predictable. The system runs with full electric power during the whole year, and recovers heat permanently. House CF curve rises with the capacity of the system up to the same size of the mCHP unit while even a bigger system is necessary to cover short but high peaks. At the same time the SOFC thermal CF curve decreases with size because with an increase of in the maximal yearly heat recovery the actual heat recovery rises just slightly.

The Figures below present comparison of the thermal capacity factors estimated for different locations.
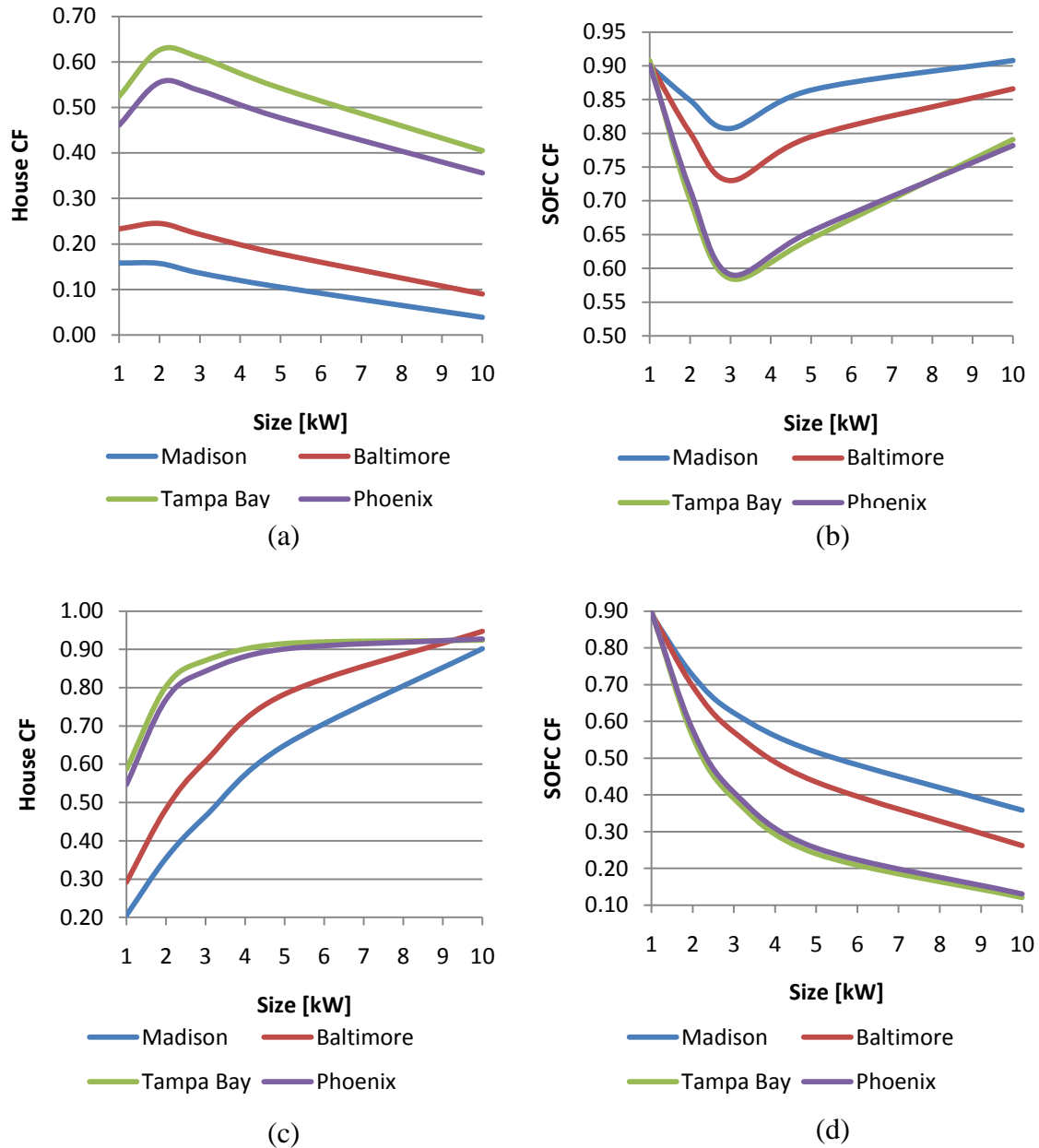
Figure 4-5 Thermal capacity factor for load following operation of (a) House, and (b) SOFC as well as for nominal output model of (c) House, and (d) SOFC.

The thermal capacity factor indicates that from the point of view of demand perspective (CF_{house})better locations are Tampa Bay and Phoenix. This is due to lower heat requirements, which can be more easily covered. The same reason makes those locations worse from the supply point of view (CF_{SOFC}). Heat demand is limited in warmer sites and of course heat recovery system is used rarely.

4.1.3 Thermal to electric ratio

The thermal to electric ratio shows how much thermal energy is used in proportion to the electricity consumed. The thermal to electric ratio of the SOFC system is the ratio of

the produced energy in the form of heat to generated electricity. TER is counted according to formula

$$TER = \frac{E_{heat}}{E_{elec}}, \qquad (4.5)$$

where E_{heat} is total heat energy and E_{elec} stands for total electricity. TER can also refer to either production or consumption. It is good when TER defined for the energy generation source and TER defined for residential demands are similar. Even if the both thermal to electric ratios were the same it would not mean that all requirements would be fulfilled. TER is an average indicator and both electric and thermal loads can have different variation during the time. This problem was already raised in the work of Krist and Gleason. They pointed out that the yearly average TER of a residential building is around 1 while for the same application, the hourly average of TER can vary between 9 and 0.2. A similar issue occurs with the TER indicator of the mCHP unit as electricity and heat generation can vary. Consumption of electricity at the dwelling can be e.g. maximal while at the same time there is no heat demand. The figure below shows the thermal to electric ratio for SOFC-based mCHP systems in all considered locations, operation modes and sizes.

(a)   (b)
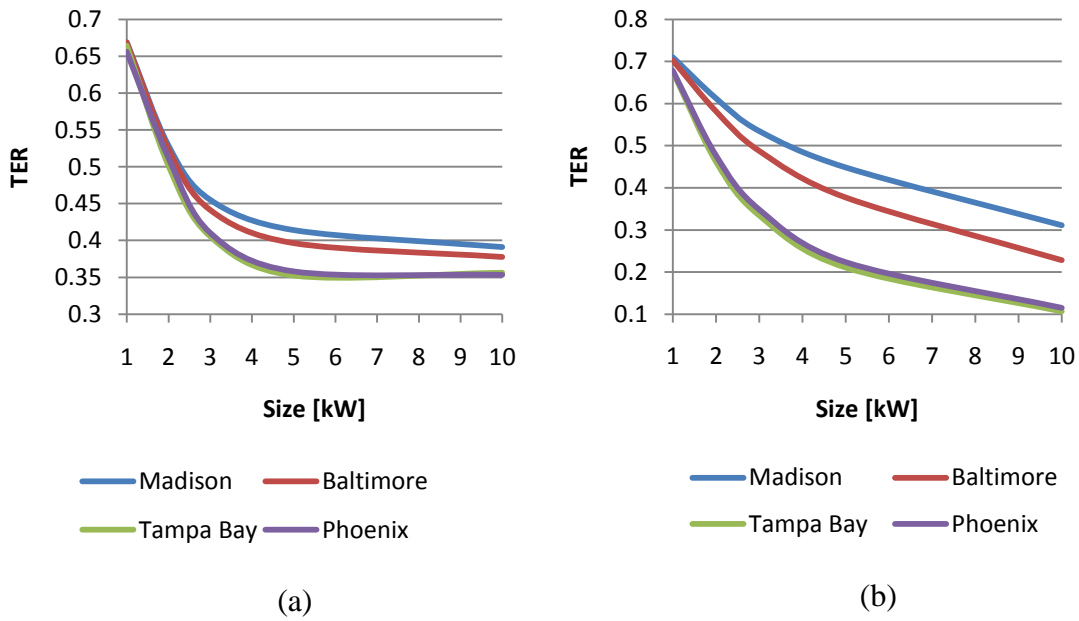
Figure 4-6 TER of SOFC mCHP for (a) load following and (b) nominal output operation mode.

The thermal to electric ratio of the systems operating in the nominal output mode decrease faster with the size of the SOFC than for the complex working according to the load following strategy. This is due to the fact that electricity production increases with the size of the system for nominal output operation whereas for the load following operation electricity generation is limited if the turn down is higher than the current demand and the production can be even smaller for bigger systems. Higher TER-s are normally in colder climates such as in Madison and Baltimore. The thermal to electric ratio decreases faster in warm climates where the electric load is much higher and total

(a)   45   (b)

heat demand is lower. TER for residential requirements is presented in the table 4-3 below.

Table 4-3 TER of the considered dwelling demand.

	Daily average	Yearly average
Madison	16.67	2.70
Baltimore	9.73	1.63
Tampa Bay	2.93	0.54
Phoenix	4.27	0.61

The thermal to electric ratio for the SOFC system is higher then the TER for load only for Phoenix for the 1 kW system. For all other system configurations the thermal to electric ratios is different from TER for loads requirements. Comparison of the thermal to electric ratio indicates that the best systems which fulfill dwelling requirements are 1 kW systems both operating in the load following mode and in the nominal output mode. The closest are the 1 kW systems in Phoenix. This does not apply to the Tampa Bay location, where the most optimal SOFC-based mCHP units are the 2 kW systems, also operating in the load following or nominal output mode.

4.2 Economical results

4.2.1 Comparison of prices

For better understanding of the economic results, simple payback time (SPBT) and net present value (NPV) are computed. The spark spread of electricity and gas prices, comparison of gas prices and net metering tariffs, and cost of electricity (COE) generated from fuel cell system were included into analysis. The spark spread price is defined here as the difference between the average daily price of electricity and the average season gas price, and is presented in the figure below. It is prepared in the form of average value according to formula

$$P_{spark\ spread} = \frac{\sum_{n=1}^{24} P_{n\ elec}}{24} - \frac{\sum_{y=1}^{x} P_{n\ gas}}{x * \eta_{electric}}. \qquad (4.6)$$

The index n relates to an hour of a day, y is a number of month and x is a number of months in a season. P_{elec} is the price of electricity in every hour and P_{gas} is the price of gas in every month. Gas prices were previously converted from \$/therm to \$/kWh. The dependence of electricity prices on seasons is taken in to account. In figure 4-7 capital letters S and W stands for the summer and the winter respectively.
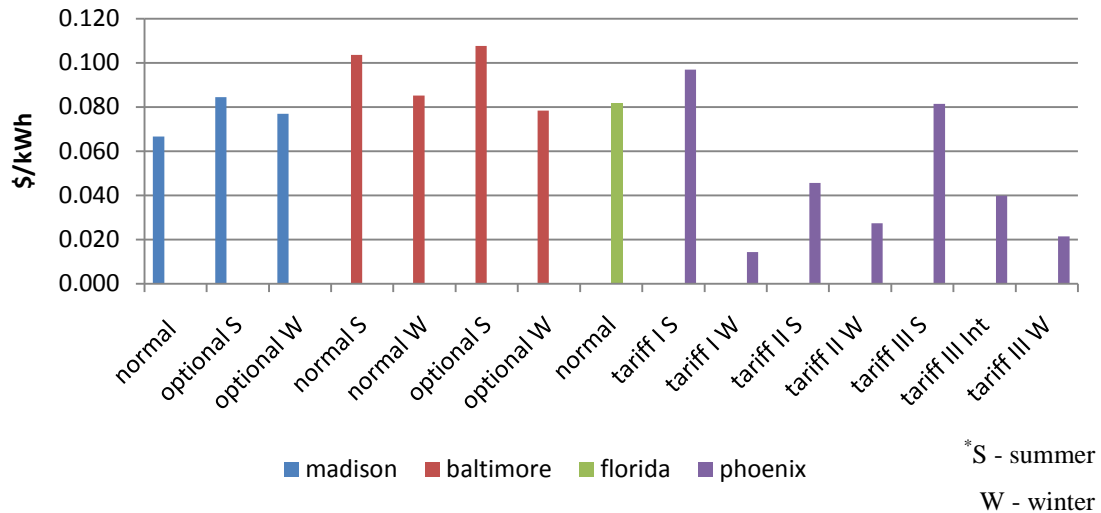
Figure 4-7 Spark spread of electricity and gas prices for different tariffs from all four locations.

It is observed that the general difference in the prices of energy media is higher during the summer season. During the winter the gas prices increase slightly due to the higher demand. Based on the figure 4-7 it is possible to say which tariffs are better and will result in higher repayment of the investment.

Another interesting finding from the comparison of prices is the relation between average gas rates and electricity prices as a consequence of the net metering tariff. In figure 4-8 the average prices of natural gas and net metering rates are presented.

Figure 4-8 Comparison of gas prices and net metering tariff

The difference in gas and net metering prices causes benefits or losses if the mCHP system is operated in the nominal output mode. Figure 4-8 shoes that in Tampa Bay as well as in Phoenix it might be reasonable to generate electricity for sale. It is also visible

that selling electricity in Baltimore is going to generate losses. The same is in Madison when the normal and winter optional tariff is applied.

Basing on Figures 4-7 and 4-8 one cannot determine whether generation of electricity from the SOFC-based mCHP is profitable. The cost of electri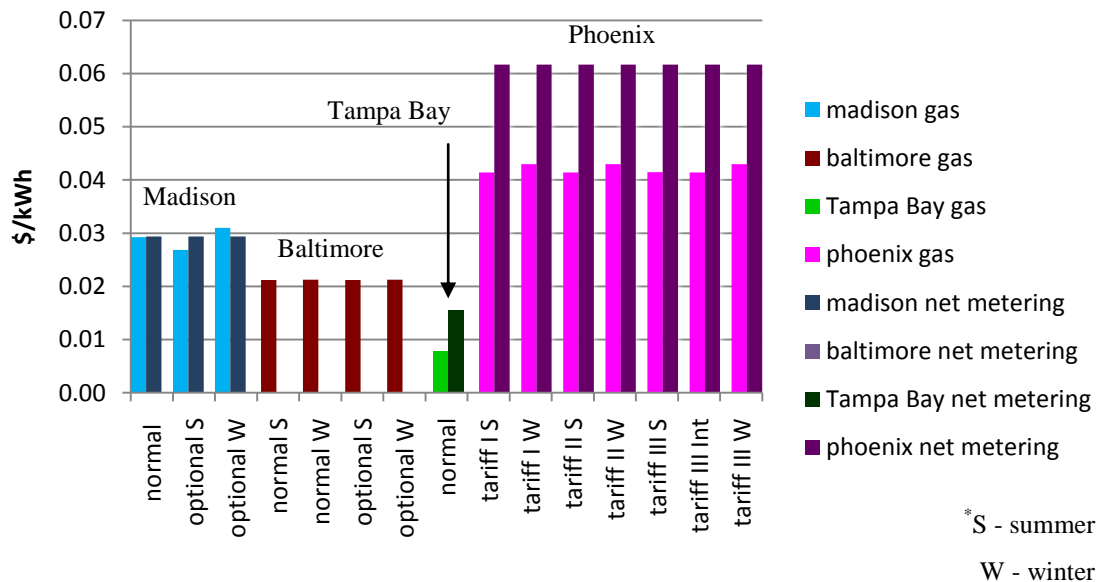city generation must be estimated to verify it. The cost of electricity production from SOFC (COE$_{SOFC}$) and from the SOFC-based mCHP system (COE$_{CHP}$) are evaluated in the thesis.

The cost of electricity production at the fuel cell is estimated as a sum of the fuel cost resulted from the gas price, the O&M cost, and capital cost. The formula for COE$_{SOFC}$ can be written[35] as

$$COE_{SOFC} = \frac{CRF * C_{system\ electric}}{CF_e * 8760} + O\&M + \frac{F_{cost}}{\eta_{electrtic}}, \quad (4.7)$$

where CRF is the capital recovery factor, C$_{system\ electric}$ is the capital cost of electricity generation system and CF$_e$ is the electric capacity factor of the considered system. The first element of equation 4.7 refers to the capital cost of the considered system. The second part of it describes maintenance of the system and is expressed by operation and maintenance costs – O&M in $/kWh. The last term applies to the fuel cost, where F$_{cost}$ is the fuel price in $/kWh, and η$_{electric}$ is the electric efficiency of the system based on LHV.

The cost of electricity generated at the mCHP system is very similar to the COE$_{SOFC}$. To the already considered terms thermal credits are added. The COE$_{CHP}$ can be calculated[35] through the formula,

$$COE_{CHP} = \frac{CRF * C_{system\ electric}}{CF_e * 8760} + O\&M + \frac{F_{cost}}{\eta_{electrtic}} - \frac{(\eta_{CHP} - \eta_{electrtic}) * F_{cost}}{\eta_{electrtic} * \eta_{htg}}, \quad (4.8)$$

where the last part stands for profits from the heat recovery system. The η$_{CHP}$ is the combined heat and power generators' efficiency and η$_{htg}$ is the efficiency of the replaced boiler. In figure 4-9 COE$_{SOFC}$ and COE$_{CHP}$ are presented.
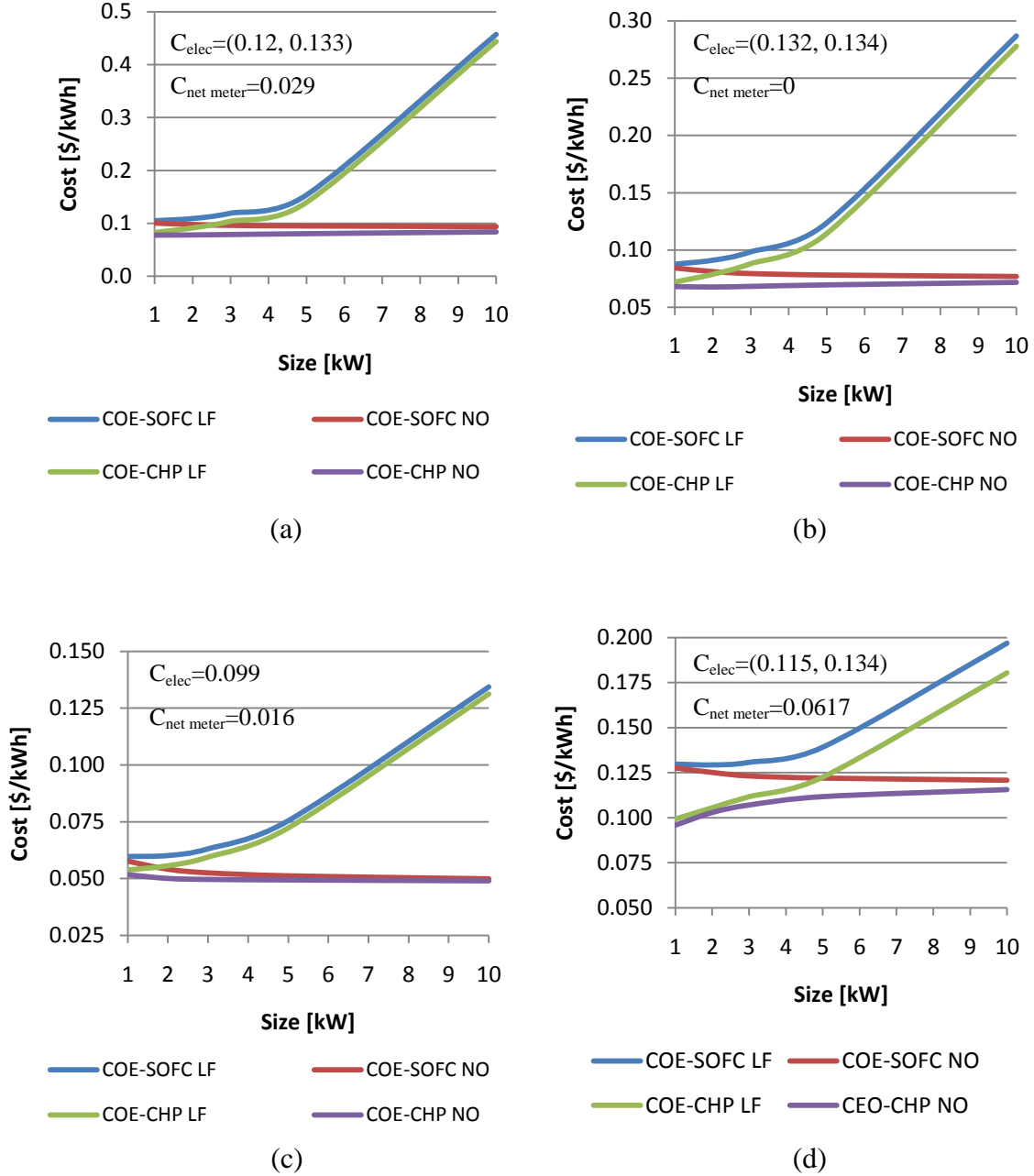
Figure 4-9 Cost of generated electricity from just SOFC and SOFC-based mCHP system in (a) Madison, (b) Baltimore, (c) Tampa Bay, and (d) Phoenix.

In figures 4-9 average minimal and maximal electricity prices and net metering rates were listed. The cost of electricity generation from the SOFC-based mCHP is generally lower than just from the SOFC. This is caused by additional heat generation in the mCHP system. For the load following (LF) operation, COE grows very fast due to the drop in the electric capacity factor of SOFC. The electrical CF of SOFC causes that the rapid increase in COE for Tampa Bay and Phoenix starts from higher capacities. The slightly decrease in the COE generation in the nominal output operation is caused by reducing the cost of the fuel cell on the capacity basis. The biggest difference between COE_{SOFC} and COE_{CHP} is caused by the highest gas prices, which are in Phoenix. The same factor causes that COE of the mCHP unit in Phoenix which operates in the

nominal output mode increases, the heat recovered from the SOFC-based mCHP system in Phoenix decreases with size.

Figure 4-9 illustrates that it is impossible to gain benefit from selling electricity to the grid from either SOFC or SOFC-based mCHPs. This indicates that the most optimal system for the nominal output will minimize the amount of electricity directed to the grid.

4.2.2 Simple payback time

One of the easiest economic parameter is the simple payback time (SPBT). The simple payback time is used as a tool for economic analyzes, because it is easy to understand and to count. Shorter payback periods often lead to wrong conclusions. If the cost savings in the subsequent years are equal, the simple payback time is counted through the equation

$$SPBT = \frac{Initial\ Cost}{First\ year's\ Operating\ Cost\ Saved}. \qquad (4.9)$$

The formula 4.9 was taken from D. Rose [36]. The value of the SPBT for the considered systems is presented below.

(a)

(b)

(c)

(d)
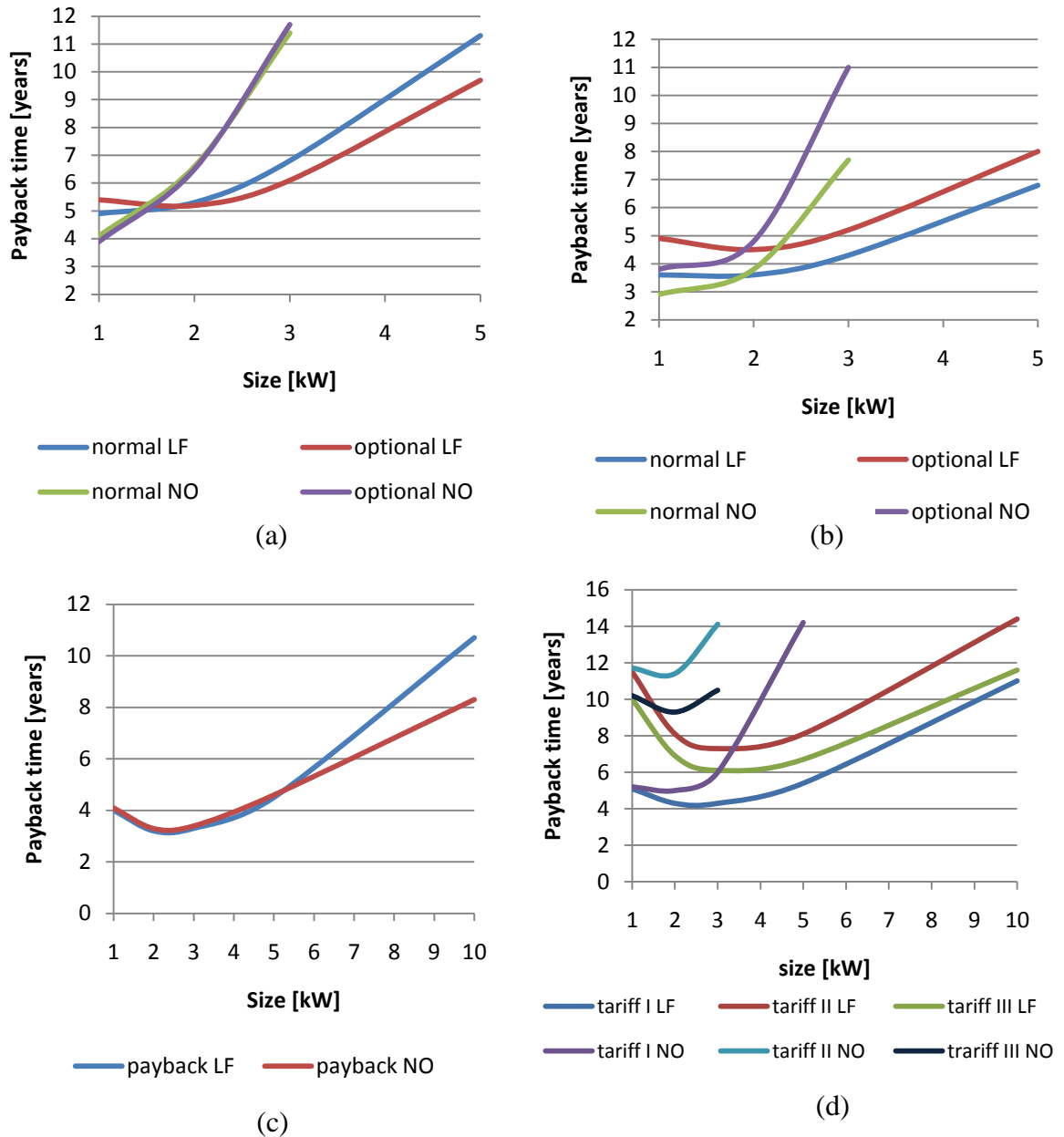
Figure 4-10 Simple payback time of the investment in the systems for the load following and for the nominal output operation modes in (a) Madison, (b) Baltimore, (c) Tampa Bay, and (d) Phoenix

The SPBT of the 10 kW system operated in the load following mode as well as the 5 kW or bigger unit operating with the nominal output exceeds 35 years, and is longer than their life time. Madison rates schedule does not make almost any difference in the nominal output operation strategy. This strategy is also preferable for the 1 kW unit. Bigger systems obtain better economic results if they operate following the load and with the optional tariff. The best system is the 1 kW unit working with the nominal output. The payback time for such a unit is 4.1 year. Reduction of the SPBT for nominal output operation for bigger mCHP units results from the difference in the COE_{CHP} and net metering plans.

In the case of Baltimore, units which operate with the nominal output whose capacity is bigger than 3 kW are not going to pay off. Also bigger SOFC-based mCHP systems following the load have a relatively long SPBT: over 25 years in the case of the 10 kW unit.. The nominal output operation mode with a normal tariff is preferable for the 1 kW units. For 2 kW systems there is almost no difference between operation strategies. The normal tariff makes the SPBT better. An increase in the payback time for the nominal operation strategy can be expected due to the different net metering plans and high COE generation. Net metering rates for Baltimore make the 2 kW system with the nominal output mode comparable to the load following system. It is because for the 2 kW size fuel cell the yearly electricity generation grows bigger than the electricity consumption at the household, and the customer starts to provide electricity to the grid. The net metering tariff of the power company in Baltimore does not assume reimbursement for net energy provided to the grid. However, if the generated energy is less than the energy consumed, the electricity which is provided to the grid has the same price as energy received from the grid.

The SPBT of SOFC based mCHP units in Tampa Bay shows that for small systems there is almost no difference between operation strategies. However for the systems with a capacity above 5 kW the nominal output operation mode gives better economic results than the following load strategy. The best unit is the 2 kW system, which operates in the load following strategy, with the SBPT equal to 3.2 year. The U shape of the payback time curve results from higher electricity consumption in Tampa Bay and use of heat generated with the SOFC mCHP at the dwellings. The highest value of the SPBT for the 10 kW system operating in the load following mode is caused by the much lower electric CF for the system and the fact that a part of the cost of electricity generated with the nominal output is reimbursed by the net metering tariff.

For Phoenix, the simple payback indicator shows that the best scenario is the load following system working with the first tariff. The nominal output mode can be considered only for smaller systems, and the lowest SPBT, equal to 5 years, was found for the 2 kW unit. The optimal capacity of SOFC-based mCHP systems for Phoenix is between 2 and 3 kW. Moreover, the best tariff, based on SPBT, is the first rate schedule. In the Phoenix, optimal capacities of mCHP units are bigger than in Madison and Baltimore because electricity consumption is also higher.

The fast increase in the SPBT for the nominal output mode in almost all location is caused by the very high costs of electricity generation.

In all cases the best system design is close to the technical optimum of the system in the given location. For better understanding of economic performance of the considered systems a net present value analysis was done.

4.2.3 Net present value

The net present value (NPV) is another economic tool to do an economic analysis of an investment. The NPV of the investment is the sum of the discounted value of future cost and benefits. In other words, the NPV is the present sum of future cash flows, where cash flows mean the difference in incomes and spendings in every year of the mCHP system's construction and operation. The net present value is expressed by

$$NPV = C_0 + \sum_{n=1}^{N} \frac{CF_n}{(1+i)^n} \quad (4.10)$$

the formula, where C_0 is the investment cost, CF_n are cash flows in year n, i is the discount rate and N is the number of year for which the NPV is counted[36]. Yearly cash flows are assumed constant through the time of operation of the system. The net present value is counted for 15 years, since this is the life time of the whole micro combine heat and power system. The life time of the fuel cell is 40,000 hours and it will be replaced during 15 years of operation the cost of replacement of the SOFC is included in the costs of operation and maintenance. The discounted rate was taken at the level of 8%. The NPV results for each location are presented in the figures below.
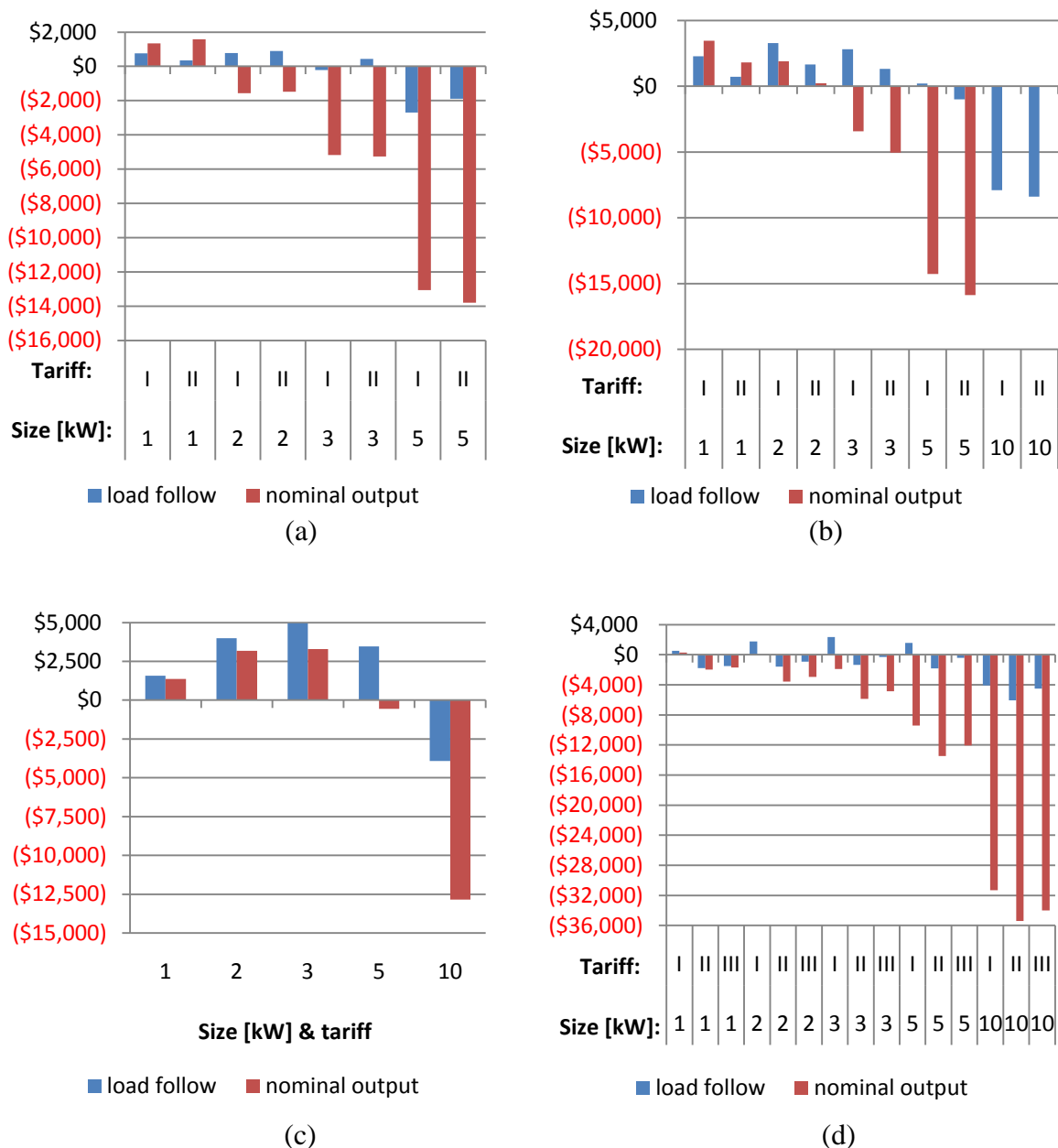

Figure 4-11 Net present value for load following and nominal output operation mode in (a) Madison, (b) Baltimore, (c) Tampa Bay, and (d) Phoenix

Patterns of the NPV of different size of technology and load operation strategy mostly depend on the cost of electricity generated by the system as well as terms of net metering plans. Another variable, which affects the value of NPV is electricity requirements and heat demand.

As shown in figure 4-11 (a) the most economical is the system with a 1 kW unit operating in the nominal output mode. The second tariff, which is optional for Madison, is better for the nominal output strategy. However for the load following operation mode normal rates are better. It appears that in Madison, most economically reasonable operation is the nominal output mode. The SOFC-based mCHP following the demand has a positive NPV not only for a 1 kW unit.

A positive NPV for a micro combined heat and power system in Baltimore is observed only for small units of 1 or 2 kW, and for the nominal output mode. The 3 kW unit from the economic point of view has a positive NPV only with the load follow operation strategy. The net present value results show that the normal tariff is better for all operation strategies. The highest economic return is expected from the nominal output operating mode and a 1 kW system working with the normal tariff schedule. The expected return is on a level of $3,470. Systems which follow the demand of the household and work according to the normal tariff provide a comparable investment return for 1, 2, and 3 kW size units.

In Tampa Bay, the best option from the economic point of view is a middle size, 3 kW system, operating in the load following mode. The net present value shows that increasing the size of system for the load following strategy, increases benefits only to some point. The maximum economic benefit from the load following system is at 3 kW unit and it is equal to $4,950. Those results are similar to the nominal output operation, although the maximum is much lower and it drops faster for bigger fuel cells. The maximum of both operation strategies is between the optimums of thermal and electrical capacity factors.

The NPV for an application in Phoenix area shows that only the first tariff brings benefits. For the first tariff, systems operating with the load following bring benefits. The optimal size of the unit is 3 kW capacity. The only system which gives some profits operating with the nominal output is a 1 kW unit working with the first tariff. Better profitability is given by a 3 kW unit. Applying the second and the third tariff does not provide any benefit for any size of the SOFC.

Comparison of the two economic indicators shows at what payback time, the investment would really pay off. The net present value also shows the real difference between tariffs. A good example of that is Madison where an analysis of simple payback time shows almost no difference between tariffs for the nominal output operation strategy, while the NPV indicators show the difference between them. The likeness between these two economic tools shows for what limit of the simple payback time the capital expenditure will return with a benefit.

The simple payback time in comparison with NPV for Maryland area confirms that units bigger than 2 kW units operating in the NO mode bring huge losses of $43,790 for a 10 kW unit. Both indicators, net present value as well as the simple payback time, show that the best unit from the economic point of view is 1 kW, if it works in the nominal output operation mode and the price of utilities is according to the first tariff. This application is going to result in a benefit of $3,290.

Similar results to Madison and Baltimore are for Tampa Bay. In Florida the only systems which caused losses are 10 kW, and NO mode 5 kW unit. The comparison of these two economic indicators shows that both indicators fit each other.

Comparison of the net present value and the simple payback time for Phoenix systems shows that the longest payback time is 5.2 years, for the nominal output mode. Systems which have longer simple payback time cause losses.

4.3 Environmental impact of SOFC mCHP unit.

Fuel cells are more environmentally friendly then most power conversion devices. They are considered that way because they are a lot more efficient than other power generators. Efficiency of the considered system of SOFC micro combined heat and power was counted as a ratio of the sum of energy delivered by the system to energy contained in the fuel. Total energy delivered by the system is the sum of produced electricity and recovered heat. Energy contained in the fuel is counted on the low heating value (LHV) basis. LHV of any kind of fuel is the amount of energy released during the combustion process with a subtraction of the vaporization of water generated through the combustion process. The equation for CHP efficiency is

$$\eta_{CHP} = \frac{E_{elec} + E_{heat}}{m_{fuel} * LHV}. \qquad (4.11)$$

Efficiencies vary with the load requirements, size of the system and operation strategy. The figure below presents efficiency for the load following working mode.

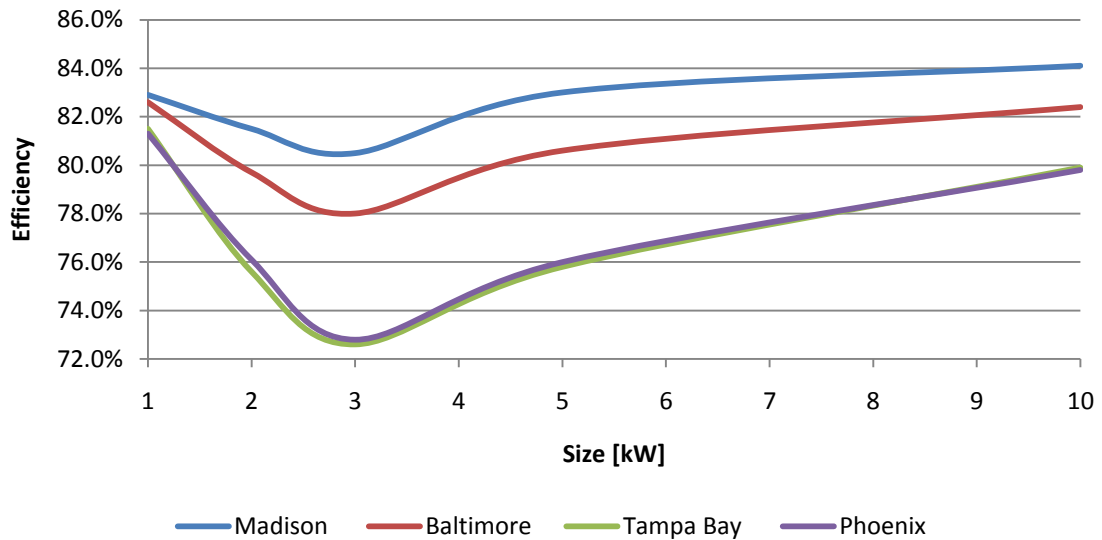*Figure 4-12 Efficiency of mCHP system for load following operation mode.*

Figure 4-12 shows that the lowest efficiency of the SOFC mCHP energy conversion system is for the 3 kW unit size. These results are very similar to results of the thermal capacity factor for the SOFC for the load following operation, although the curves are smoother. The comparable results indicate that there is a big effect on the system

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efficiency from heat recovery and generation. The electric capacity factor of the SOFC makes efficiency curves smoother rather than steep.

The change in efficiency of the mCHP system for nominal output strategy work is shown in figures below.
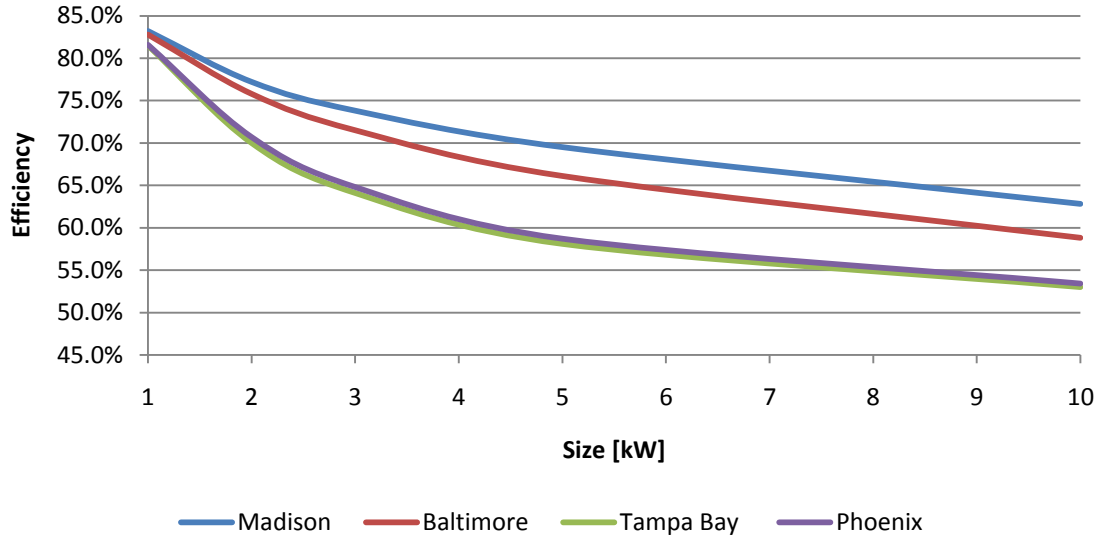

Figure 4-13 Efficiency of mCHP system in nominal output operation mode.

A heat recovery system has a big effect on the efficiency of total energy conversion in a the nominal operation mode. Efficiency patterns of the system are shown by similar curves of the thermal capacity factor of the SOFC for the nominal output mode. Efficiency of the mCHP system operating in the NO mode is generally lower than for a the load following mode.

The solid oxide fuel cell based micro combined heat and power system, due to its high efficiency has also lower CO_2 emissions. The figures below show the amount of CO_2 which through the use of mCHP is not emitted into the atmosphere. Calculations for this were carried as a difference in the emission from the original source of electricity and heat generation, and the sum of emissions from SOFC and grid electricity as well as heat generation for covering additional requirements. Emissions from the primary electricity source were counted as multiplication of energy consumption and the average of state emission per kWh. The equation looks like this:

$$CO_{2\ emission\ form\ grid} = E_{elec\ total} * CO_{2\ emission\ average}. \qquad (4.12)$$

Where $E_{elec\ total}$ is the total grid electricity consumption in kWh, $CO_{2\ emission\ average}$ is the average emission of carbon dioxide from the grid energy mix, and it is counted in t CO_2 per kWh. Emissions from heat generation, as well as from the SOFC, result from the use of fuel. This was computed from the emissivity of natural gas. The results of these calculations are presented in the figures below for load following and nominal output operation modes, separately for all locations.
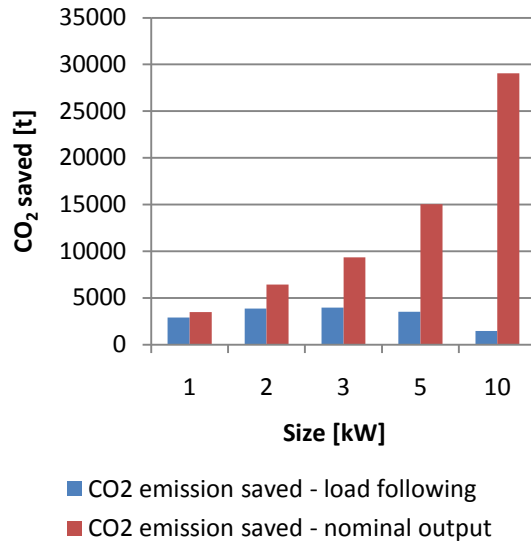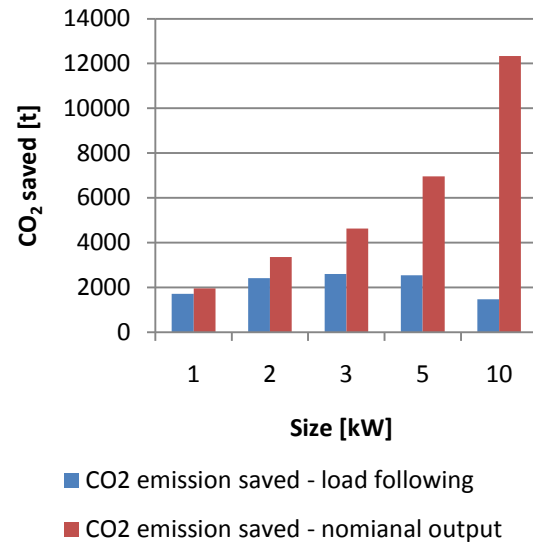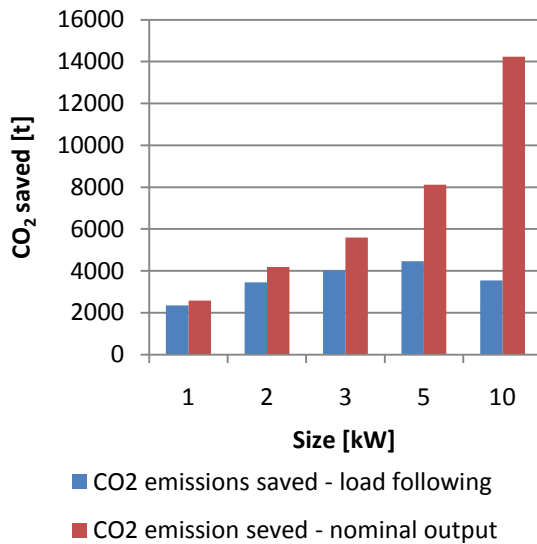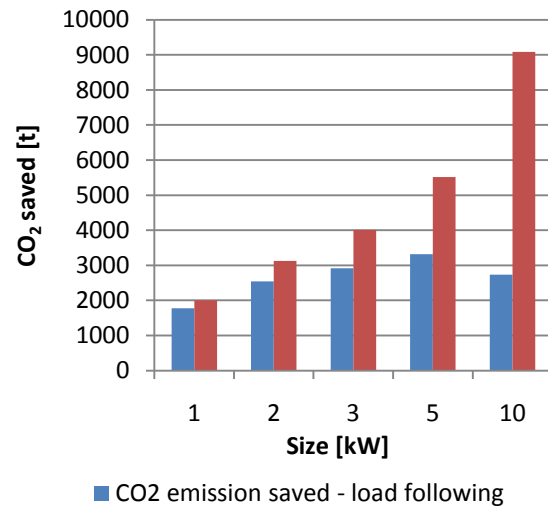
Figure 4-14 CO₂ saved emission from mCHP in load following and nominal output operation in (a) Madison, (b) Baltimore, (c) Tampa Bay, and (d) Phoenix

The maximum of saved CO_2 in Madison for load following is at a 3 kW system. For the nominal output operation mode it is a lot higher, equal to 29,000 t CO_2, for a 10 kW system. The Baltimore maximum is at 3 kW for the load following working strategy and 10 kW for the NO operation, although CO_2 emissions are lower than in the Madison location. The Tampa Bay peak of saving CO_2 emissions in the load following operation is moved, and it is for a 5 kW system. The nominal output operation strategy has a peak of saved CO_2 emissions for the 10 kW, as usual. Savings of CO_2 emissions for the load following working mode are higher than for Baltimore and on a similar level for Madison, as well as the second operation schedule. In Phoenix, the saved CO_2 emissions have a peak at 5 kW for load following and at 10 kW for the nominal output operation mode. Savings for the load following working strategy reach values of 3,000

tons of saved carbon dioxide. The NO savings of CO_2 are higher than for the LF operation mode, except the 1 kW system in Baltimore, where the difference is just 50 tons.

In all locations the peak of the electric capacity factor for the load following operation modes is the same as for the CO_2 emission saving peak. This is so because the main CO_2 savings are the biggest issue due to the electricity load. Heat recovery, which decreases the use of a primary heating boiler, increases savings of a CO_2 emission for a smaller size of the system. The nominal output work strategy has the advantage of emission saving from electricity and is more reasonable. It is also visible that a higher thermal capacity factor of SOFC for NO prevents carbon dioxide emissions. This occurs due to the higher heat recovery volume.

5 LOCATION VS. ECONOMIC CONSIDERATION

The economic comparison of SOFC-base mCHP units operating in different locations and with different tariffs, makes results unclear. It is hard to distinguish which location is better and which is not. Different prices and various load requirements make it very hard to determine the cause of economic and environmental results. The comparison of different locations working with the same rates schedule solves this problem. The electricity and gas prices were taken from the Tampa Bay location.

5.1 Economic results

The simple payback time for the SOFC mCHP working in the load following mode in all locations is shown in the figure below. The SP time of a 10 kW unit in Baltimore is over 30 years and in Madison over 115 years, which is why they were not tagged in the figure.
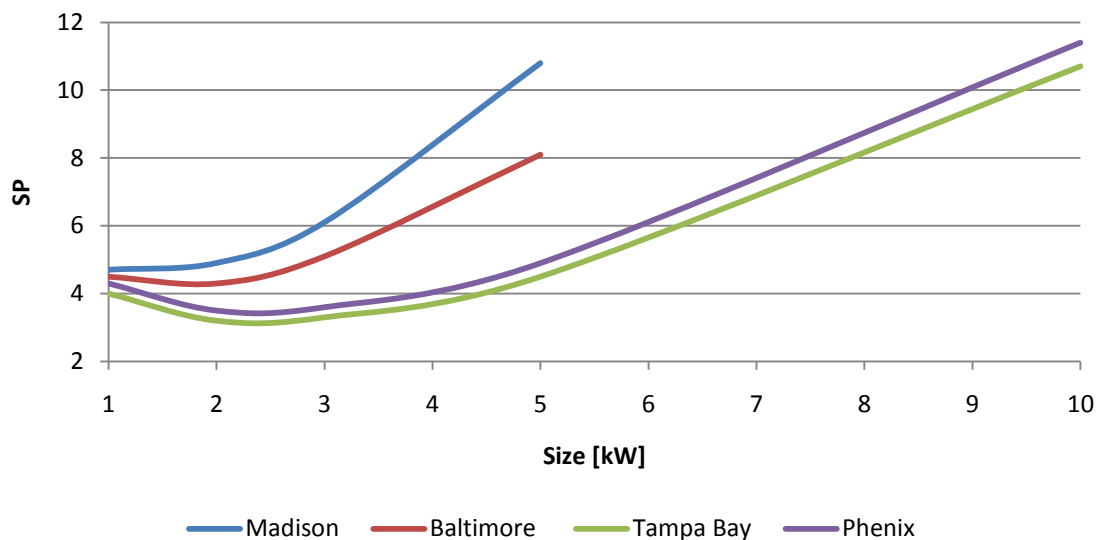
Figure 5-1 Simple payback time for the same tariff in different locations for a system operating in the load following mode.

The optimal system for load following operation is in Tampa Bay and it is based on a 2 kW fuel cell. Figure 5-1 shows that the best location for a load following system is in Tampa Bay. Phoenix load requirements give very similar results.

It is also visible that the minimum of the simple payback time is due to both maximum heat recovery and maximum electric generation. It means that the system must be matched as precisely as possible to both heat and electric demand in order to reach the best economic performance.
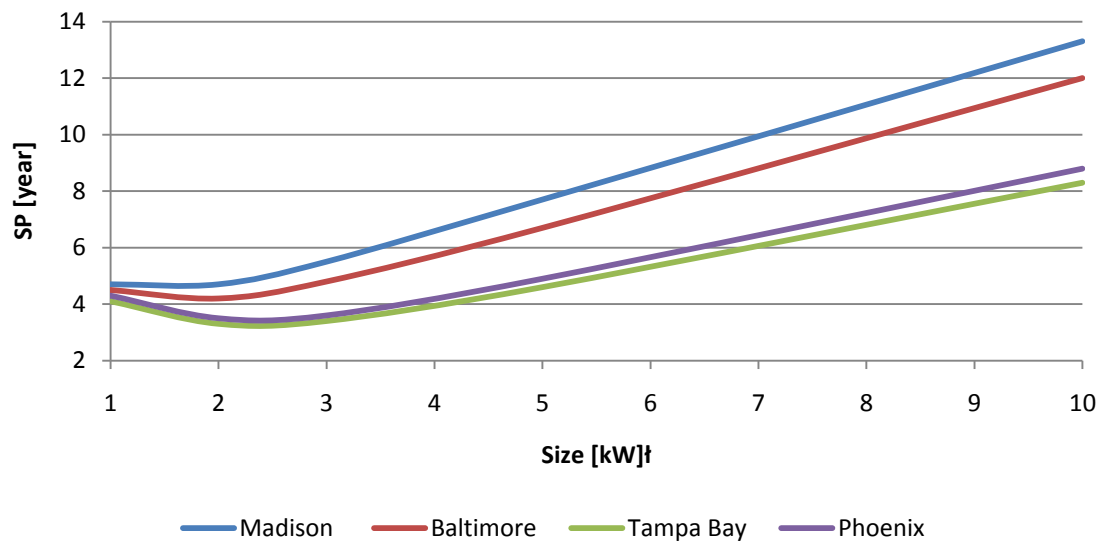
Figure 5-2 Simple payback time for the same tariff and different locations of system operation with nominal output.

The values of the simple payback time for the nominal output operation strategy are very similar to the results of the SPBT time for a load following system. In both cases the SPBT for smaller units do not differ much for all locations. The lowest SBPT is found for the system applied in Tampa Bay, and the minimum value of the SPBT is characteristic of the mCHP unit of $2 - 2.5$ kW capacity.

Results of the net present value for SOFC based mCHP systems, working in four locations and using the same tariff, are presented in two figures below. The first for the load following operation mode (a) and the second for nominal output working strategy(b).
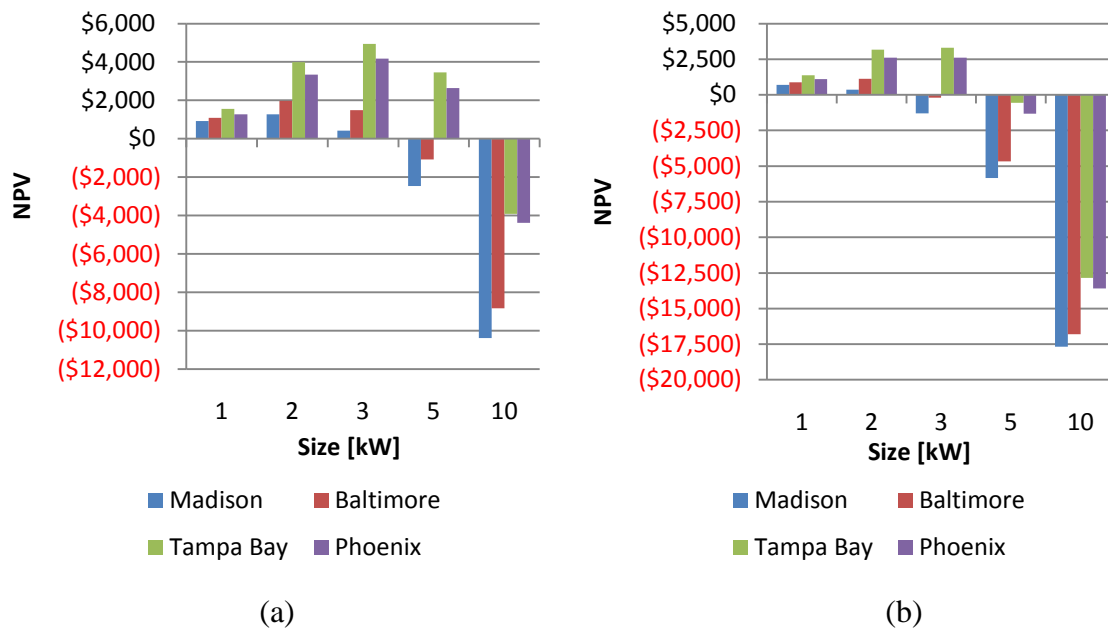
Figure 5-3 NPV for different locations, at the same tariffs for (a) load following and (b) nominal output.

The results confirm the earlier presented results for the simple payback time. They show that for the load following system the best load requirements are in Tampa Bay and those from Phoenix are just slightly worse. The net present values of a system working with the nominal output are very similar, which confirms the results of the SP time. It is also visible that the difference between Madison and Baltimore compared to Tampa Bay and Phoenix is not very big, which is caused by heat demand helping to achieve better economic results in colder location..

This analysis shows which loads are the best for different operation modes. The comparison of these results with economic analyses of the system for different tariffs shows that the energy prices in Madison compared to the rates from Tampa Bay are worse. Better performance is visible for the nominal output operation, with original tariffs for Madison. However, the load following operation with Madison loads is better for the Tampa Bay tariff.

The Baltimore normal tariff is better for load following operation as well as the nominal output mode compared to the Tampa Bay tariff. Also, the optional tariff in Baltimore is better for the load following work strategy. Although the results for the nominal output mode are very bad with the optional tariff from Baltimore and the Tampa Bay tariff is better for such operation.

Phoenix tariffs are the most diverse. The original rate schedule in Phoenix for load following systems hardly makes any profits: for all systems working with tariffs II and III economic results are negative. Tampa Bay rates are much better. Only for the 10 kW system size the NPV is on the minus side. Moreover, comparison of net present values for different locations which use the same tariff shows that Phoenix loads aren't the worst. The profits are slightly lower than the Tampa Bay results. The NO operation of a system in Phoenix with original rates is pointless, because the original tariff with the

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nominal output mode has a negative NPV indicator. The only exception is for the first tariff and a 1 kW system. However, the results compared to the NPV of Phoenix demand and Tampa Bay rates are worse.

It seems that Tampa Bay is one of the best locations considering its rates and the difference between loads in colder and warmer places is minor. For both operation strategies the preferable loads are from warmer places such as Tampa Bay and Phoenix, where heat demand does not make much difference and most of the profit is from electricity. Although for the nominal output mode colder locations are very close.

5.2 Environmental results

Another indicator which is changing between locations is the CO_2 emission rate from the grid. In all locations it is slightly different and because of that, except efficiency, it affects the amount of CO_2 emitted to the atmosphere. The comparison of between saved CO_2 emissions in different locations for two operation modes is presented below.
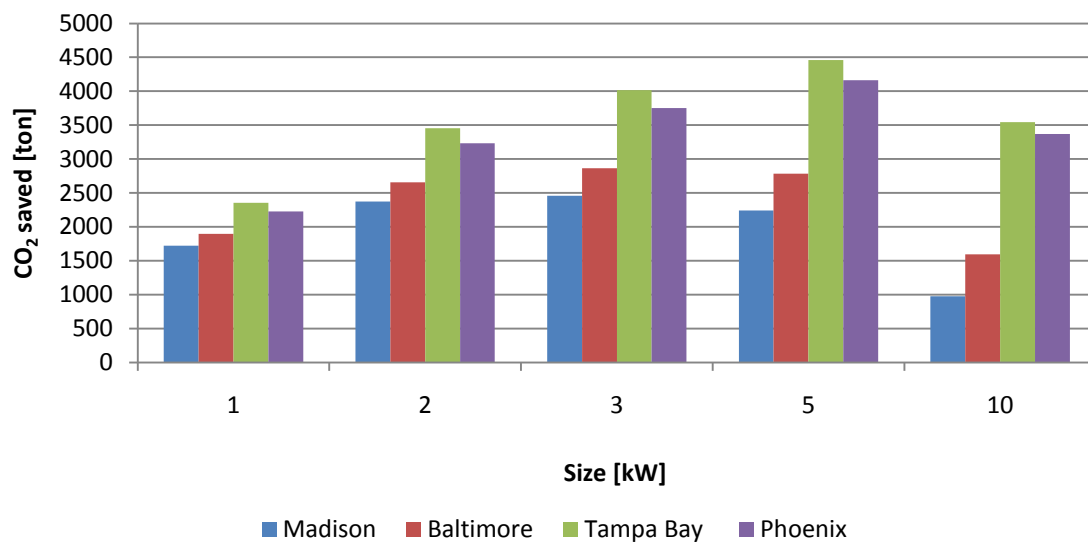
Figure 5-4 comparison of CO_2 emission saved for load following operation mode

The highest emission savings for a load follow system are for Tampa Bay. The pattern of warm and cold climates can be observed: for warmer climates emissions saving are higher. Also, an electric capacity factor peak is visible and it makes CO_2 emission savings peak for Baltimore and Madison at a 3 kW system, as for Phoenix and Tampa Bay at 5 kW.
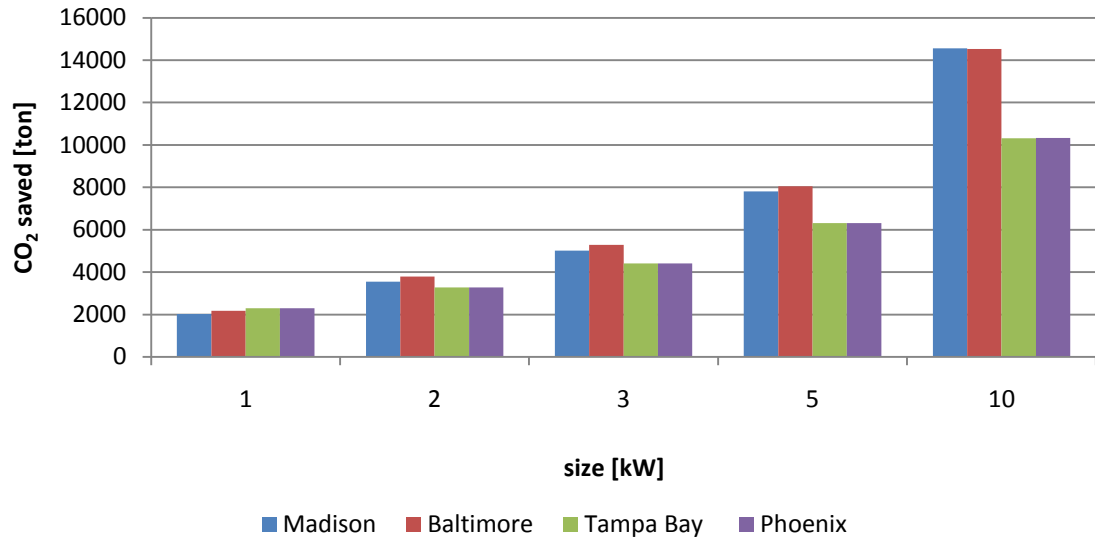
Figure 5-5 comparison of CO_2 emission saved for nominal output operation mode

The CO_2 emission saving for the nominal output operation has opposite results. For such an operation mode, the system working on requirements from colder climates saves more carbon dioxide emissions than loads from warmer locations. Moreover, in the colder location, emissions saved are higher than for the load following operation mode. This is caused by higher heat generation from the SOFC. The CO_2 emissions are lower for warmer location loads, such as Tampa Bay and Phoenix. This is caused by much higher electricity generation and, at the same time, only a small growth in heat generation. The best load requirements are for the Baltimore location with the Tampa Bay emission grid rate. Tampa Bay load requirements result in very similar emission savings in comparison to Phoenix demands.

6   CONCLUSIONS

6.1   Results summary and conclusions

In summary, there is a number of approaches to optimize SOFC-based mCHP system. The most basic is finding a system which will cover most of the application demand. This is much harder for a combined heat and power system since demand for thermal energy can be different than for electricity. Moreover, the CHP units normally have different responses for changes in the generation of electricity as well as heat. Another problem with finding the most optimal system is the unit capacity factor which shows how long the unit is in operation. This is very important because sometimes, although the system covers all the demands, its CF is around 10%. In finding an optimal system, it is very important to evaluate its impact on the environment. Additionally, after coming out with the technical and environmental optimum, it is very important to check the economic results of the system. All these issues relate to all four locations and should be addressed separately.

6.1.1 Madison optimal system

The electric capacity factor of a house in Madison for the load following operation has a maximum of 90% for a 3 kW system. In the same time the electric CF of a fuel cell is the highest for the smallest system. The thermal capacity factor of a house in load following operation mode is the highest for the 1 kW and 2 kW system equal to 16%. On the other hand the highest use of potential heat recovered from the fuel cell is for 10 kW unit. The thermal to electric ratio for such working strategy is the highest for a 1 kW unit and it is equal to 0.67. This result is far from the TER of a dwelling demand which is equal to 2.7. The optimal system from technical point of view was chosen to be a 2 kW capacity. It was decided through the compromise of a different technical indicators.

For the load following operation mode maximum efficiency for the SOFC-base mCHP system in Madison is for a 10 kW of 84%. The lowest efficiency of the system is for the 3 kW system, which is 80.5%. However the highest CO_2 emission reduction was obtained for a 3 kW unit. The optimal system from the environmental approach was chosen to be a 2 kW system. This was caused by close to maximum CO_2 emission savings value as well as slightly higher efficiency of 81.5%.

The economic results of the SOFC-base mCHP in Madison for the load following mode are not satisfactory. The minimum SPBT for the installation is 4.9 years. This is for a 1 kW unit according to normal tariff schedule. For a bigger fuel cell more profitable is the optional tariff. The minimum SPBT for the SOFC mCHP system according to optional tariff is for a 2 kW unit and it is equal to 5.2 years. The highest net present value is for a 2 kW unit regardless the chosen tariff. Although, the optional rate schedule makes such a system more profitable. The optimal system, based on the economic indicators was chosen to be a 2 kW unit. For such a system chosen tariff is the optional rate schedule.

The nominal output operation changes many features of a system and because of that it has different results and a different optimal size. The house's thermal CF is the highest for a 10 kW unit. On the other hand the SOFC CF for the same size is the lowest. The highest thermal CF for a SOFC is for a 1 kW unit. The thermal to electric ratio indicates

that the closest to residence TER is 1 kW unit. The optimal size for nominal output operation mode was chosen to be a 1 kW unit. As it reaches maximum for two indicators.

The highest efficiency of the SOFC mCHP system for the nominal output mode is for a 1 kW unit and the lowest efficiency is for the 10 kW system. On the other hand the CO_2 emission savings have a different pattern from the efficiency. The biggest emission savings are for the 10 kW unit and are over 29,000 tones of CO_2.

Economical performance for nominal output operation strategy system in Madison demonstrates the lowest payback time of the 3.9 year, for the 1 kW unit. For all system sizes the optional tariff is better. The NPV confirmed results of SPBT, so the best from economical point of view is the 1 kW system according to the optional tariff.

Based on these results the best operation system for load following operation mode is the 2 kW unit with optional tariff. The weakest feature of this system is the system's efficiency of 81.5%. The optimum for nominal output operation was not so easy to find. The 1 kW system shows preferential values of technical and economical factors. Although the avoided emissions as well as thermal capacity factor of a dwelling indicates 10 kW unit. Considered all indicators it was chosen that the best system for nominal output operation mode is the 1 kW unit and this system similarly to load following SOFC-based mCHP should be according to optional tariff.

6.1.2 Baltimore optimal system

The micro combined heat and power system base on SOFC in Baltimore if working in load following operation mode has an optimum of electric capacity factor for a 3 kW unit. Although, the thermal CF for such operation indicate that better system is with smaller unit such as a 2 kW. Also, the TER indicator shows that closer to the residential TER are system with lower capacity. Base on this results the technical optimum of a 2 kW was chosen.

The efficiency for the SOFC-based mCHP system working in load following mode of a 3 kW system is also the lowest. The highest efficiency has a 1 kW unit. On the other hand the highest emission savings of CO_2 are for the 3 kW unit.

The economic results for load following system in the Baltimore are not convincing. The shortest simple payback time is for the 1 kW and 2 kW system for the first tariff. Although the NPV is highest for a first tariff for a 2 kW unit. According to that, the optimum system is to be a 2 kW unit which operate at first tariff.

The nominal output operation mode has a thermal capacity factor of residential application the highest for a 10 kW unit. Although, the SOFC thermal CF is for this unit the lowest. The best fuel cell thermal capacity factor in nominal operation mode is for a 1 kW unit. The TER of a fuel cell for a 1 kW system is the closest to the desire thermal to electric ratio for a dwelling. The technical optimum was chosen to be a 1 kW unit, based on compromise between technical indicators.

The system efficiency in nominal output operation mode drops with size for nominal output operation strategy. Although, that savings of the CO_2 emission are rising with increasing capacity of a system. This two factors make impossible to chose a right system for Baltimore based only on the environmental aspects.

The economic tools of analyze help answer the question which size of system it optimal for nominal output operated system in Baltimore. The SPBT indicate that small system

are much better and the best is a 1 kW unit, which operate according to first tariff. The NPV results presents that in nominal output mode economically the best is a 1 kW system, which use the first tariff.

In conclusions the load following system optimal fuel cell is 2 kW unit. The optimal load following system is using the normal tariff. The optimal nominal output system is a 1 kW also working according to the normal tariff, since it has the highest NPV, efficiency, TER indicator and also thermal capacity factor.

6.1.3 Tampa Bay optimal system

The load following system in Tampa Bay area have an optimum of the electric capacity factor at a 5 kW. Although, the SOFC CF is decreasing with size of fuel cell and the best is for a 1 kW unit. The 2 kW system is the best from a thermal capacity factor of a house. Similarly to electric CF of a fuel cell, the thermal CF of a SOFC has an optimum for a 1 kW unit. The thermal to electric ratio of a SOFC system indicate that, the best system capacity is 2 kW. The differences in optimal sizes for different technical aspect make it difficult to chose the best size of the SOFC-based mCHP.

The efficiency of the SOFC-based mCHP system working in load following strategy has a minimum for a 3 kW and is the highest for a 1 kW unit. Although that, the highest CO_2 emission savings are for a 5 kW system. The optimal system just from environmental indicators is hard to find.

The minimum of the SPBT is for the 2 kW unit. Although that, the NPV for load following system is the highest for the 3 kW system. The economic results alone do not indicate which system should be chosen as an optimum of a SOFC-based mCHP for Tampa Bay region for load following operation mode.

The nominal output operation SOFC thermal capacity factor of a house has slightly different patters form load following working strategy. It reach its optimum for a 5 kW unit. The best thermal CF of a SOFC-based mCHP is for a 1 kW unit. Although that, the TER is dropping very fast with a size of a system and the optimal size is between a 1 kW and 2 kW unit. Low thermal CF for fuel cell at high capacity makes the best system to be a 3 kW unit.

The efficiencies of SOFC-based mCHP system, which operates in nominal output mode, are also dropping with a size of FC. The best system, which has a size of a 1 kW, has the efficiency of 82%. Although that, CO_2 emissions savings for the 5 kW are more than three times higher than for the 1 kW and the maximal emission savings has a 10 kW system. The optimal system size from environmental point of view is 5 kW unit.

The economical tools such as the SPBT indicate that the best nominal output system in Tampa Bay, it is 2 kW system. Although, the results of NPV indicate 3 kW unit as an optimal one. Based on the economic indicators, the optimal size of the SOFC-based mCHP was chosen to be 3 kW unit.

Based on these results it is really hard to interchangeably answer which system is the most optimal as a load following unit in Tampa Bay area. It seems that for load following mode the 3 kW system is the best, because it is very good from the economical and environmental point of view, this size of a system is a compromise between electric CF and thermal CF of Tampa Bay load following system. Slightly easier to find is optimum for the nominal output system. The best SOFC-based mCHP system operation with nominal output is, the same as for load following, a 3 kW unit.

6.1.4 Phoenix optimal system

The load following optimal system for SOFC-based mCHP is 5 kW what was indicate by the electrical capacity factor. Although the 1 kW system is an optimum of electric CF for the SOFC. The thermal capacity factor of a SOFC has a minimum for the 3 kW and maximum for 1 kW unit. On the other hand the maximum of the system thermal CF is for a 2 kW fuel cell. The best size in Phoenix for load following mode based on TER is 1 kW system. The optimum from technical point of view for load following work conditions was chosen to be a 3 kW unit.

The highest efficiency in Phoenix is for the 1 kW system. The biggest CO_2 emission savings are for the 5 kW system. The optimum size of SOFC-based mCHP system was chosen to be a 3 kW unit, the same as based on the technical index.

The best economical results for load following system is a 3 kW system working according to the first tariff. Although, the lowest simple payback time is for a 2 kW fuel cell. The best system was chosen based on the highest NPV for load following mode. The other tariffs, despite the first one, are not provide any returns from the investment, according to the NPV.

For the nominal output operation mode the highest thermal CF is for a 10 kW. Although the SOFC thermal capacity factor is very low. The TER indicator is very high for lower size units. It drops very fast with a size of fuel cell. It was chosen that the technical optimum of a SOFC-based mCHP is a 3 kW.

For the nominal output operation strategy efficiency drops very fast with increasing size of a system. It is similar to the TER of the SOFC-based mCHP, the highest is for 1 kW unit. The highest emission savings of carbon dioxide are for the 10 kW unit. This results makes determination of a system environmental optimum very hard for nominal output operation strategy.

The best results of SPBT for nominal output mode is for a 2 kW unit operation according to first tariff. The best tariff is a first rate schedule, compared to second and third one. The results of the NPV are positive only for 1 kW unit working according to first tariff The best system from economic point of view was chosen to be a 1 kW unit operating with the first tariff.

It is hard to decide which system is most optimal load following system. It seems that the closest to optimum is a 3 kW SOFC power mCHP unit operating according to first tariff. For nominal output operation finding the optimum, which would be good from all sides is impossible. It was chosen that the best size of a system is 3 kW fuel cell working according to first tariff. Although such system is not good from economic point of view but acceptable based on technical and environmental indicators.

6.1.5 The best location

The technical indicators, such as a capacity factor, an efficiency and the TER do not change with a different tariffs. With the rates schedules change results of an economic as well as the CO_2 emission savings are different due to different grid emissivity. The optimal location for SOFC-base mCHP was chosen based on comparison of four different locations for the same tariff from Tampa Bay.

The results show, that for Tampa Bay loads requirements are the shortest pay back for all sizes of the SOFC for load following operation mode. The NPV indicator is consistent with SPBT results. Moreover, the highest CO_2 emission savings were found

for the same loads requirements. Although that, system operate on Tampa Bay loads has the lowest efficiency. Electric capacity factor of a house is the highest for the Tampa Bay demands, which means that the electric load pattern of this location is the best covered by SOFC-based mCHP system. The maximum of SOFC electric CF is the highest for Tampa Bay demands as well as the thermal capacity ratio for house. The TER required by dwelling is the closest to this which is provided by SOFC-based mCHP for Tampa Bay loads.

The comparison of indicators for load following operation shows that the best location for SOFC-base mCHP system is Tampa Bay location.

For the nominal output operation mode loads requirements from all four locations according to the Tampa Bay tariffs have different results. The economical results indicate that a system operating on loads from wormer locations such as a Tampa Bay and Phoenix is better. The net present value indicates that slightly better investment return will occur once again for the Tampa Bay loads. On the other hand the results of CO_2 emissions savings are higher for operation according to colder locations. Slightly better in comparison between Madison and Baltimore in this field are results for the Baltimore demands. The Baltimore loads are better from Madison demands in thermal CF for dwelling, but worse for SOFC thermal CF. The TER factor is higher for Madison system compared to Baltimore. Although that, closer to the house TER for this two locations are indicators form Baltimore. The closest to house TER are results for demands from warmer locations especially for Tampa Bay loads. The highest efficiency has system working on the Madison loads.

Different results of technical, environmental and economic analysis makes hard to chose the optimal loads requirements for nominal output operation mode. The Baltimore requirements were chosen as an optimum for the nominal operation of the SOFC-based mCHP system.

The summary of the most optimal SOFC-base mCHP system is made in table 6-1.

Table 6-1 The optimal systems in each location and the best load requirements.

Location	Load following	Nominal output
Madison	2 kW optional tariff	1 kW optional tariff
Baltimore	2 kW normal tariff	1 kW normal tariff
Tampa Bay	3 kW	3 kW
Phoenix	3 kW first tariff	3 kW first tariff
Loads comparison	Tampa Bay loads	Baltimore loads

The smaller SOFC-based mCHP units are preferable in colder locations, such as Madison and Baltimore. This is caused by the lower electricity usage. The heat regeneration from the fuel cell system is low compared to electricity generation, which is confirmed by low thermal to electric ratio. The warmer localization has an optimum of the SOFC-based mCHP system with higher capacity. This is primary caused by the higher electricity usage due to higher cooling requirements. Although, because of small thermal requirements the optimum for Tampa Bay and Phoenix is lower than the optimal electric capacity factor.

The efficiency of a SOFC-based mCHP system is generally lower for warmer location than for the colder. This is caused by the lower heat requirements, which make combined heat and power system less efficient. The operation strategy do not affect comparison of efficiency between warmer and colder location. The operation strategy affect general patterns of efficiency. For the load following operation due to turn down ratio the efficiency of a system is higher for bigger units, in opposite to nominal output mode.

The operation mode affect the CO_2 emission savings. The load following mode systems has a peak of CO_2 savings for electricity peak. The nominal output working strategy has higher emission savings for bigger fuel cells. This results are due to much higher electricity and heat generation through the nominal output mode compared to load following working strategy.

The comparison of SOFC-based mCHP systems with the same tariff that despite of operation mode the best form economic point of view are requirements from Tampa Bay. This is caused by the highest SOFC electric capacity factor, moreover high electric capacity factor of house, and thermal capacity factor of a dwelling.

6.2 Future recommendation for research

This work answer many question but still leave many unanswered question. It need more exact analyze of residential loads, especially electric load and domestic hot water demand. Moreover it would be much better to make optimization for more detailed loads. In this thesis sensitivity analyze was not performed. Such analyze would exact answer for what price level of utility and system investment is economically preferable and has investment return. It would be also interesting to see the results of SOFC-based mCHP combined with other heating system recovery and heat storage. Another very interesting issue would be an analysis of the SOFC-based mCHP system of a bigger capacity for a complex residential dwelling or smaller office building. Small change of fuel cell feature would allow to make sensitivity analyze of fuel utilization in such system. This is even more interesting since unused fuel from SOFC can be burned and used as thermal energy if needed.

6.3 System propose modification

Model used in this thesis is very good although there can be made same modification. First modification would be more exact data for residential loads. Residential demand, especially of electricity is changing very fast and analyze based on hourly average of heat and electric demand can be no precise enough.

Secondly economic analyze, which assume constant price of utility is not very precise. Proper economic examination requires prediction of future prices of utilities. The future prediction should be carried both for the gas as well as for the electricity prices.

Moreover system technical specification could be done more precise. Technical aspect of system can make impossible for real system to work in this way as it was assumed in the model. In example it is not sure if fuel cell response for fast changes of electricity load could be fulfilled. Although including this aspect in the thesis would make it more complicated and it would increase necessary time for research. Also such precise model would work better for more exact demand.

6.4 SOFC-based mCHP system – possibilities in Poland

It was pointed earlier that the Madison location has similar climate to Poland. This assumption allows to postulate that the optimum found for Madison location is also the optimum for a Polish SOFC-based mCHP system. The optimal size of the SOFC-based mCHP system in load following operation for Poland would be a 2 kW unit. The optimal system working in nominal output mode would be 1 kW system as it was evaluate before, but the load following mode will probably give higher profitability of the investment.

However for Polish conditions of the house requirements are different from those in the USA. The electricity consumption is lower mainly due to lack of cooling demand. On the other hand it can be assumed that at a modern single family house where air conditioning is in use during the summer, the electricity consumption can be similar to the dwelling in Madison.

The biggest difference between the Madison and Polish conditions are prices of utilities. In Poland the gas prices are higher as the electricity prices from the grid are lower. However the implemented system of certificates of origin supports cogeneration based on gas and gives additional revenue.

The results of CO_2 emission savings would be also slightly different due to different emissivity, which was assumed for a electricity from the grid. The CO_2 emissions savings which are due to heat recovery from the fuel cell would not change.

Presented differences shows the possibilities for future analyze of a SOFC-based mCHP unit for Polish conditions. Although the results of these thesis present that it is possible to received satisfactory results from such analyze.

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Appendix A