COMBINED HEAT AND POWER - TECHNOLOGY REVIEW AND ANALYSIS FOR A RESIDENTIAL BUILDING

By

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ABSTRACT

This thesis intends to show the current state of Combined Heat and Power Systems and highlights the different aspects of the technologies. A manufacturer directory was developed and the theoretical principals for planning and analysis of a CHP system are described.

In the second part, a case study is analyzed for residential application in the USA. Three Micro-CHP systems are chosen: Otto engine, Stirling engine, and fuel cell. Also two locations, Chicago and Atlanta, are selected to represent the northern and southern region. The calculations are based on models in TRNSYS and BHKW Plan. The results show, that the fuel cells, represents the heat demand in the best way. Environmentally, each system shows improvements of over 50% CO_2 reduction. From the economic perspective none of the systems can offer a return of the more investment compared to the conventional heat and power generation.

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LIST OF ABBREVIATIONS

CHP, Combined Heat and Power

CHPP, Combined Heat and Power Partnership

CEC, Commission for Environmental Cooperation of North America

COP, Coefficient of Performance

DOE, Department of Energy

EIA, Energy Information Administration

EPA, Environmental Protection Agency

HHV, Higher Heating Value

HVAC, Heating – Ventilation – Air Conditioning

IEA, International Energy Agency

IEEE, International Electrical and Electronics Engineers

ITC, Investment Tax Credit

LHV, Lower Heating Value

MCHP, Micro Combined Heat and Power

NREL, National Renewable Energy Laboratory

ORC, Organic Rankine Cycle

ORNL, Oak Ridge National Laboratory

RAC, Regional Application Center

ROI, Return on Investment

NOMENCLATURE

A	Area	[m^2]
a	year	
CLF	Cooling load factor	
CLTD	Cooling load temperature difference	[°C]
c_p	Specific heat	[kJ/kgK]
$H.G._L$	Latent heat gain	[kW]
$H.G._S$	Sensible heat gain	[kW]
No	Number of people	
$\dot{m}$	Mass flow rate	[kg/s]
Q	Heat capacity	[kW]
Q_L	Latent Load	[kW]
Q_S	Sensible Load	[kW]
Q_{total}	Total heat capacity	[kW]
P	Perimeter	[m]
P_L	Power Lamp	[W]
SC	Shading Coefficient	
SHGF	Solar heat gain factor	[kWh/m^2]
$T_{average}$	Average room temperature	[°C]
T_g	Ground temperature	[°C]
T_i	Inside temperature	[°C]

T_o	Outside temperature	[°C]
T_s	Supply temperature	[°C]
T_{set}	Set temperature	[°C]
U	Overall heat transfer coefficient	[W/m^2K]
$\dot{V}$	Volume flow rate	[m^3/s]
w_i	Inside humidity	[g/m^3]
w_o	Outside humidity	[g/m^3]

CHAPTER I

INTRODUCTION

Economic health of a nation primary depends upon the mineral and energy resources and agricultural production along with many other factors. The per capita consumption of electricity in a community plays a vital role in improving the living conditions, industrial production, and thus the standard of living. More than 70% of the electricity produced in most of the nation is provided by the use of fossil fuels, such as coal and natural gas. Combustion of these fuels produces greenhouse gases such as CO_2, NO_X or SO_2. These gases are found to cause the global warming phenomenon. Climate change and extreme weather patterns are attributed to global warming. The energy required for heating and cooling of buildings in industrialized nations is significant, and 72% of electricity produced in the U.S. is utilized for HVAC operation of buildings. The electricity demand is increasing 1% per year. Since 2010, the U.S. has become the second largest consumer of electricity after China. The average annual electricity for U.S. residential consumers is 11,496 kWh.

The current situation in the energy sector is characterized by a constant rise in energy consumption on the one hand, and diminishing resources of fossil fuels on the other. This allows for a constant rise in costs. Furthermore, the rise in energy consumption has a negative impact on the environment due to increased greenhouse gas emissions. In order to overcome these problems, intense efforts are needed for energy consuming devices. A low cost and more efficient renewable energy conversion has a key role to address these needs in the future. A CHP system uses various fuels and has a potential to make a quantum leap in energy efficiency by producing forms of energy outputs, the shaft power and heat energy.

The major portion of this energy consumption is typically utilized in heating and cooling of building space and for producing domestic hot water. A CHP system primarily consists of a prime mover such as steam or gas turbine, or reciprocating engine, and a heat energy recovery system. Depending on the capacity of the system and type of fuel used, the components employed in the CHP system vary. Generally reciprocating engines are used for small capacity units. The CHP system is capable of providing heat energy and electric power simultaneously from a single fuel source, thus increasing overall energy efficiency of the CHP system. In winters, the system of appropriate size is capable of providing sufficient heat energy to meet the building heating loads, domestic hot water and electric power demand. In certain cases, the heat energy produced from CHP systems can also be employed as an input to an absorption chiller to meet the cooling load during the summer. Due to increase in temperature observed in recent times during summers, the utilities are under pressure to meet the electrical demand of their customers with a potential for brownouts and blackouts to occur during the time of peak loads. CHP systems can serve as an efficient, side-management tool to meet the electrical loads. CHP systems will also serve as a valuable and powerful tool for implementation of small grid applications.

Principle of Combined Heat and Power Systems

The combined heat and power generation is the simultaneous conversion of energy to produce electricity or mechanical shaft work and useful heat energy by use of one primary fuel source.

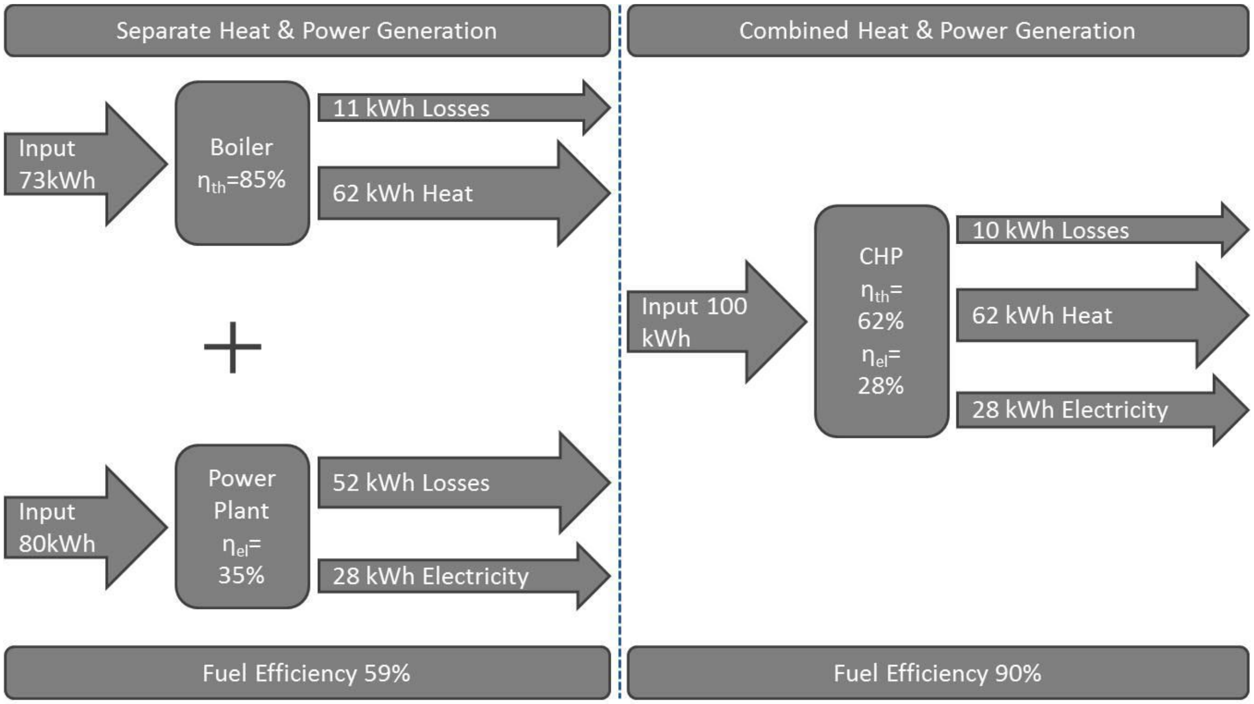


Figure 1 Comparison of Combined and Separate Heat and Power Generation

The mechanical shaft work produced from thermodynamic processes occurring in the engine is converted into electrical power by use of an electrical generator. The heat energy generated by this engine is typically discharged into the environment and thus wasted. The combined heat and power recovers this heat energy which can be employed for space heating, hot water, or chilled water through use of an absorption chiller for space cooling. Generation of two energy forms (electricity and heat, in form of steam or hot water) from one single primary source is also called co-generation. Generation of three different forms of energy is called tri-generation, i.e. generation of electricity, steam or hot water and chilled water. The fuel consumption of CHP systems compared to separate production of electricity and hot water or steam is more efficient. Exclusive power generation has efficiencies around 30 to 45%, but CHP has an overall efficiency up to 90% and higher, as shown in Figure 1, thereby reducing the greenhouse emissions. The difference in efficiency can be higher for larger CHP plants.

CHP Design Considerations

Proper sizing and design are crucial criteria for the use of CHP and thus for the economic calculation of such a system. If a CHP system is too small, the energy cost savings cannot be realized. However, if it is too large, it has to run often under part-load conditions. Such part-load conditions result in lower efficiency or time mode operation, which means frequent start and stop modus of the unit. Different boundary conditions generally require individual design and planning of a CHP system. Therefore, technical and economic parameters are used for the exact analysis of a CHP plant.

The approach to calculate heating and cooling load is different for existing and new buildings. New buildings can be simulated with software when the results are at hourly demand values. The applicable considerations and calculations are described in more detail in chapter III. For an existing building a simulation can also be performed if all necessary data is known. Bigger buildings, especially commercial or industrial buildings, use a building monitoring system, in which a history of consumption data is reported. Unfortunately, this is often not the case for smaller buildings. A review of the utility bills is often helpful. However, it only gives a vague monthly break down.

Based on the integration of hourly heating values, an annual load curve can be obtained. An example is shown in Figure 2. All performance values for the year (e.g. hourly values) are sorted according to size (e.g. thermal load). This relationship is referred to as an annual load duration curve. The units on the y-axis represent the percentage of the maximum heat demand, the units on the x-axis represent the hours over the year. The area located below the line indicates the annual heat demand. The design of a cogeneration plant for 100% of the maximum heat load is irrational; a recommended value is 30% of the maximum load. However, electricity, which can then be used or fed into the public grid, is produced only during these operating hours. The recommended value is about 6,000 operating hours per year to generate enough power to be able to refinance the CHP.

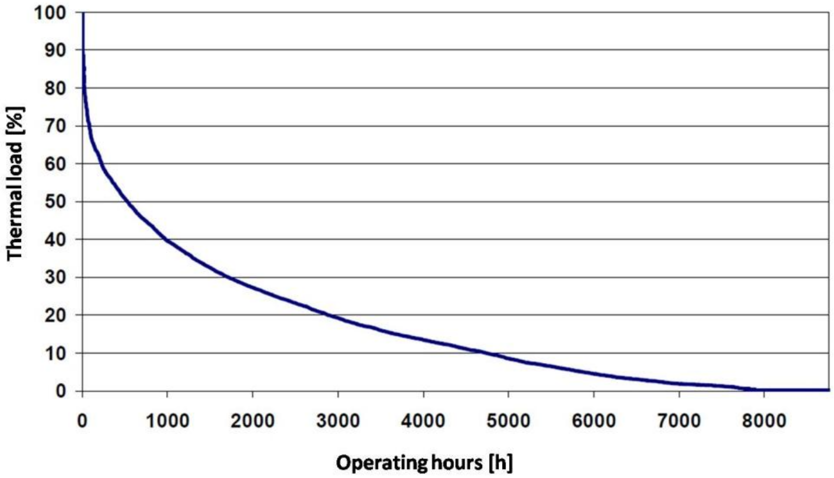


Figure 2 Example of Annual Heating Load Duration Curve

Classification can be made in the area of the operation design of CHP systems. Generally, three different design variants are possible [23]:

- Power-oriented
- Heat-oriented
- Cost-based

In a Power-oriented design, the system is created with adjustments to the power demand. If the electricity demand deviates from the electrical output, the CHP unit can be reduced. If not, the overly high or low power supply gets compensated by the public grid. In this case the heat production is the by-product.

Conversely, for the heat-oriented design, operation is adjusted to the heat demand. If the heat output is lower than the demand, an auxiliary system has to start up. If the heat demand is less than the thermal output of the CHP unit, it can either be reduced to part-load conditions, switched on and off, or generate excess heat. This excess heat can be stored to a certain degree in thermal storage tanks. However, excess heat should be avoided, as discharging the product into the environment reduces the efficiency of the system.

The cost-based design considers the case with minimum overall costs. CHP systems are most efficient under full load, thus a system design to cover the base load should be created. The heat peak load is covered with an additional boiler and the electrical peak load is covered by the grid. Generally, full load hours are desirable to allow the high investment costs to be paid back as soon as possible.

Another important aspect of CHP is the load control, which can be realized as cycle mode or rolling mode. If operating in tact mode, the system either operates at rated load or is turned off. If a system operates in rolling mode, the CHP device is not able to operate under full load at all times. When the demand decreases, the system operates only in the partial load range which, due to technical and economic reasons, is only possible within certain limits. Thus, the efficiency of the plant is reduced.

Furthermore, three different supply concepts are distinguished:

- parallel
- emergency power
- standalone operation

In general, micro-CHP units are operated in parallel with the power grid. This means that the CHP plant feeds excess power into the grid, and receives electricity from the grid when the demand is higher.

If there is no connection available to the grid, CHP units can be driven in a standalone mode. Typical applications are isolated homes, shelters, etc. The CHP provides the building with electricity and heat. In this case, the electricity supply has priority. In addition to the CHP system an inverter and a battery are required for standalone operations.

The emergency power concept is a combination of parallel and standalone operations. In power mode, the CHP unit operates in parallel with the main power source while the network is available. If a failure occurs in the grid, the CHP takes over the power supply. The CHP will initially be separated by an external isolating switch from the network. The CHP is turned off and then started up again in standalone operation. This type of electrical integration is used especially for applications where power and heat are essential.

Need for a large Spark Spread

CHP units are characterized by the simultaneous generation of usable heat and power in a constant proportion. As a result, two types of operation modes for CHP systems are possible:

- Heat-oriented
- Power-oriented

In a heat-oriented mode, the cogeneration system will rise to its upper limit of the heat demand curve; the peak boiler covers the remaining heat demand. The generated electricity is either used within the same time or fed into the public power grid. The demand for electricity during the downtime of the CHP and any additional requirements are supplied by the electric grid. In Figure 3, the purpose of the buffer can be recognized. It allows continued operation of the cogeneration system at specific load when the demand for heat goes down. If the buffer is fully charged, the performance limit of the CHP will be reduced. If that lower limit is reached, the CHP is turned off and the heat demand is provided by the thermal storage tank.

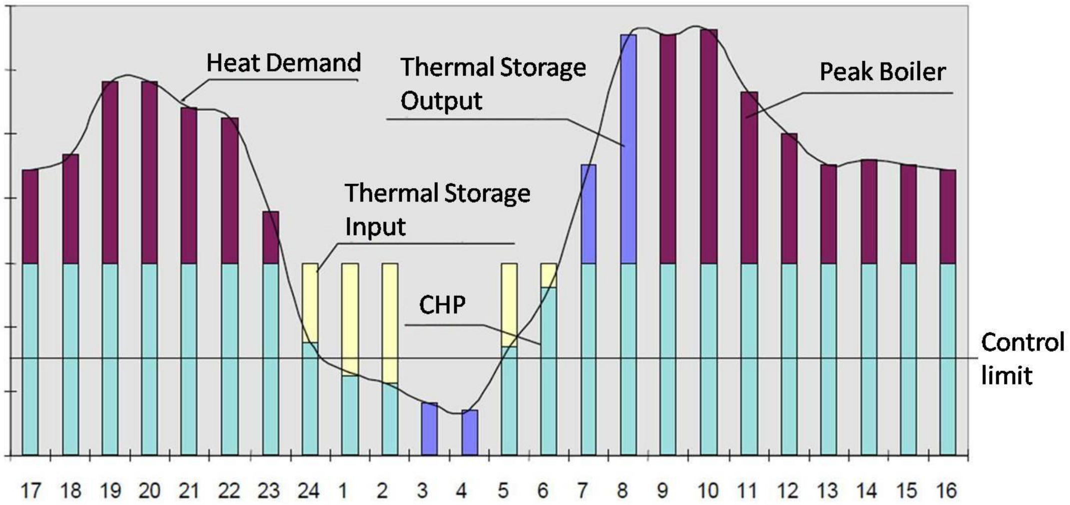


Figure 3 Heat oriented Operation [34]

The design of the CHP unit for power-oriented operation is based on the power demand and is similar to a heat-oriented mode. The CHP operates to its upper limit of the power demand curve, and an additional demand is compensated by the public grid, see Figure 4. Examples of power-oriented operations can be found mostly in the commercial sector. The CHP may form the central part of the operational power supply if an expensive electric power demand is present. From an ecological perspective, this mode is only useful if the heat generated can be completely used. Excess heat must be stored in a thermal storage tank or dissipated to the environment.

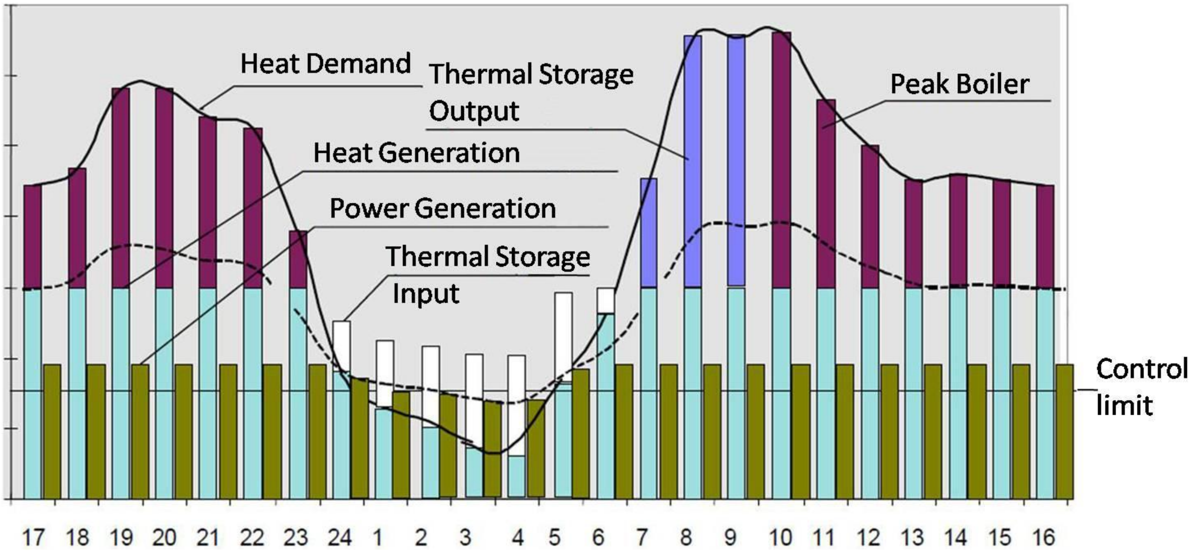


Figure 4 Power oriented Operation [34]

The next step is the calculation of the spark spread, as it also includes the cost perspective. The spark spread is the theoretical margin of a power plant. All cost, such as acquisition, operation, or maintenance costs must be covered by the spark spread. If the spark spread positive then the price of the electricity is higher than the fuel price. Thus, the power plant operates profitable. Negative numbers mean that the power plant is not operating cost-effectively and the power plant is losing money. The spark spread is calculated as followed:

$$\text{Cost of Fuel} = \frac{\text{Cost (\$)}}{\text{Usage (kWh)}}$$

$$\text{Cost of Electricity} = \frac{\text{Cost (\$)}}{\text{Usage (kWh)}}$$

$$\text{Spread Spark} = \text{Cost of Electricity} - \text{Cost of Fuel}$$

In Figure 5, the different operation strategies are displayed. With an increasing slope, more electricity can be produced by using the recovered heat. Point A represents the perfect balance between electrical and thermal energy. This, however, is a theoretical point, which can almost never be achieved. Point B and D fulfill the electrical requirements. But, the thermal energy output of point D is too low, which would require an additional heat source. At point B the thermal output is too high. Thus, excess heat is produced and wasted. Opposite production occurs at points C and E. Here, the thermal requirements are met, and the electricity output is too high or too low. Operation at point E should be avoided. If the excess electricity cannot be sold the operation is not economical.

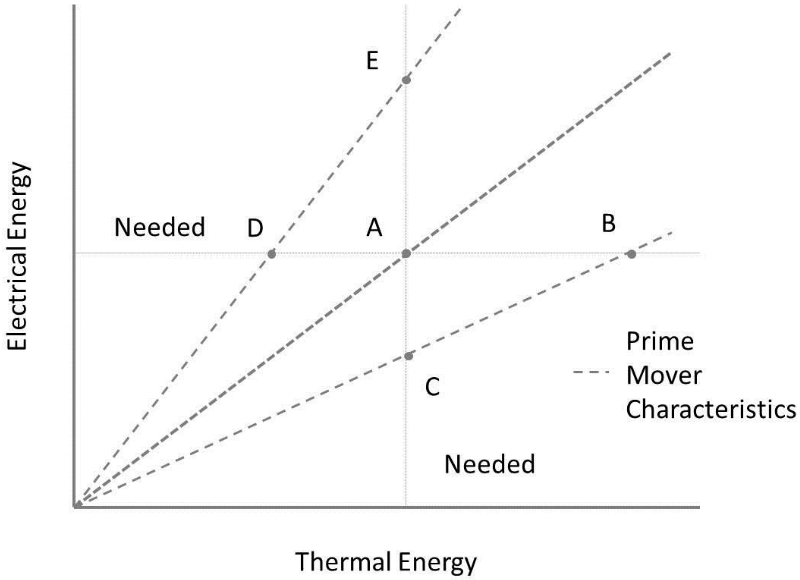


Figure 5 Operating Strategies for CHP Systems [21]

The spark spread measurement is important because it helps utility companies to determine their bottom line profit [24]. Determination of the economic feasibility of a CHP system is more involved than just calculating the spark spread [21]. The principles of economics are described in detail in chapter II.

CHAPTER II

ECONOMIC ASSESSMENT OF CHP SYSTEMS

The purchase of a CHP plant, even in the low power range, is typically a more expensive investment than a regular heat supply system. Therefore, the capital expenditure budget needs to be studied before making such an investment.

A characteristic of an investment is that cash flow is generated and financial resources are borrowed and paid off on either mid to long term ranges. To assess the financial impact of an investment, different calculation methods are established. A distinction is made between static and dynamic methods of investment appraisals. Table 1 displays the different methods.

Table 1 Economic Calculation Methods [8]

Static methods	Dynamic methods
• Cost comparison • Profit comparison • Static payback calculation • Return of investment calculation	• Net present value method • Internal rate of return method • Annuity method • Dynamic payback method

In this paper, the strengths and weaknesses of the individual calculation methods are not discussed in detail, but recorded in the literature [8], [33]. In general, the static methods do not consider the time structure of payments, e.g. no distinctions are made whether payments incur today or in five years. To obtain a better decision basis, more than one calculation method is often used to evaluate an investment. In this paper, the annuity method and the method of dynamic payback are described in detail, since these two methods give the most detailed understanding of the economic situation.

Annuity Method

The main idea of the annuity is to evenly distribute payments associated with an investment during the operations lifetime [8]. The annuity method allows the combination of one-time payments / investments and current payments with the help of an annuity factor, during the observation period, T. The payments represent the following costs: fixed capital costs, usage costs, operating costs, and others.

Depending on the project and the operation, the deposit payments may have the same results as the disbursements described above. This is especially true for capital-linked deposits, if such subsidies or grants are awarded for investments or for tax benefits. The difference between the deposit annuity and disbursement annuity gives the cumulative annuity. Small-scale CHP plants are usually not designed for the goal of generating profit. Therefore, it is the rule that the best system is the one which costs the least.

For CHP systems the assignment of separate costs for electricity and heat is inappropriate. For an economic analysis, the capital, fuel and operating costs and revenues from the CHP operation are compared with the use of a separate power and heat supply. The annual heat production cost is measured from the annual cost of the CHP system after deducting the value of its produced electricity. The annual costs represent the sum of fixed capital costs, usage costs, operating costs, and other costs. The usage and operating costs also depend on how much of the CHP production is used to cover the demand for heat and electricity.

Capital related costs:

The key is to distribute the investment payments, considering interest and compound interest over the system’s lifetime. Therefore, the annuity method is applied, where investment costs are divided into equal annual amounts. The annual capital-related costs - the annuity - consist of two parts: One is the percentage of recovery of invested capital and the other part is the interest rate, which represents the interest on the outstanding payments at the beginning of each period [8]. The following equations are used for the calculation [10]:

Interest factor	$q = (1 + p/100)$
Interest rate	p [%]
Lifetime	n
Annuity	$a=\frac{q^n\cdot(q-1)}{q^n-1}$
Investment	I
Annual capital-related costs	$C = I * a$

Investments:

The following components constitute the major investments of using a CHP system [14]:

- CHP system
- Peak boiler
- Thermal storage tank
- Technical integration of CHP
- Power supply
- Construction measures
- Fuel storage
- Additional costs for planning and approval

It should be noted that the components of an existing heat supply system can be used. Thus, for example, an existing boiler may be used as a peak boiler, or an existing hot water tank can be integrated into the CHP system.

Useful lifetime:

For the calculation of the annuity of the individual investment, the useful lifetime is critical. The calculated lifetime ends before required repair, overhaul and maintenance costs for the renovation of individual system components are more expensive than the acquisition cost. From a technical point of view it makes sense to put the useful life equal to the lifetime. Under the security aspect of an investment, however, the choice of a shorter useful life, and therefore the distribution of costs over a shorter period are reasonable to minimize the risks [34].

Interest rate:

In addition to the life span, the discount rate is of particular importance for the economic analysis. The amount of the discount rate depends on the type of financing for the planned investment. In a fully self-financed project, the discount rate is set at least at the level of the interest rates of a particular capital market investment. The interest rate for debt financing determines the lower limit, if money needs to be borrowed. Since the resulting investments and the useful time can be risky, an additional risk factor can be added in both cases. Mixed financing from equity and debt can be used with an interest rate that is set by the discount rate for equity as well as the invested capital. [8] The discount rate and the useful lifetime are determined based on the economic analysis and the specific point of view of the planner or operator.

Consumption related costs:

The consumption related costs, also referred to as fuel costs, are composed of the annual fuel costs for the CHP system and the boiler, as well as the annual power supply costs. When natural gas is chosen as fuel some tax systems may include a demand charge in addition to a pure energy price.

Operating costs:

The annual operating costs include maintenance and personnel costs. The maintenance refers to maintenance, inspection and repair. Very often full service contracts with the manufacturer are completed for CHP modules. These agreements provide a comprehensive service at a fixed rate per kilowatt hour of electricity produced. This includes all work which is generally understood to be necessary for the smooth operation of a system and includes inspection, all maintenance and repair, spare parts and supplies (except fuel). A major overhaul is usually also included in long-term contracts. Besides the good predictability of such contracts, another advantage is that the execution of all work on the CHP is transferred to the seller, and the technical risks are covered, e.g. an engine failure, by the full maintenance contract. [33]

Review of self-power generation:

The value of the electrical energy generated in CHP systems (for both: power and energy) is calculated as follows:

Costs of additional electricity acquisition

- Additional costs for electricity purchases

- Cost of backup power purchase

+ If needed: credit for excess / residential electricity supply

= Value of own power generation.

The additional electricity acquisition costs arise if the power company has no self-generated power supply. The electricity, which is still needed after installation of a CHP plant as additional power is called excess - or residual electricity. Costs for backup power may arise when a higher power rating is used than ordered. These costs are dependent on the rate for backup power ordered from the utility companies. When supplying excess power into the grid, revenues can be credited.

The energy generation characteristics need to be known for the CHP system to evaluate the self-generated electricity. The superposition of the power load profile and the electricity generation by the CHP system defines the fractions of electricity fed into the grid and the additional electrical power needed. For this calculation, a simulation based on hourly values is inevitable. Specialized software for the design of CHP plants simulates typical load curves for calculated usage.

For the evaluation of electrical energy generation, the knowledge of individual power delivery terms and the conditions of the energy companies is crucial. There is usually a price difference for the agreed day and night rate, also called high- or low-rate, and established winter and summer time rates. With the recognition of the hourly flow data and the linkage with the different price conditions of the utility companies, the cost of the residual current reference for possible back-up power, and the revenues for the supply of surplus power can be calculated. These cost calculations can then be compared with the cost faced by procuring electricity more traditionally.

Heat generation cost and comparison with central heating:

The annual cost of the CHP systems are calculated as described in the Section “Capital related Costs”. After deducting the self-generated electricity, the annual heat production costs are, calculated as follows:

Annual costs of heat-und power generation

- Current value of generated electricity

= Annual heat production costs

For alternative heat generation with a boiler, the annual heat production costs can also be calculated from fixed capital, demand/ consumption-bound, operating, and other costs. Dividing the annual heat production costs by the annual amount of heat generation results in the specific heat generation costs [$/kWh] for both systems. According to the criteria of economic efficiency, those power plants are selected, which have the lower annual heat production costs. [33]

Dynamic Payback Calculation

This payback method is one of the most frequently used methods for the capital budgeting process. The payback period length is a measure of the investment risk and is another criterion for assement of a system. The owner must decide between the static and dynamic payback calculation. For the static payback period, which is determined by the initial investment, the later resulting net cash flows which will be recovered, regardless of the timing and the resulting interest rate effects. The neglect of pay back timing is a major criticism for this type of calculation because payments at different times are not easily compared with each other.

The dynamic calculation of amortization is derived from the capital value method and eliminates this criticism. The annual cash flows are discounted to time zero and the dynamic payback period is reached when the cumulative present value of cash flows is equal to the initial investment. Thus, the fact is taken into account that future payments are worth less than previous payments. [8]

For CHP units, whose aim is self-supply and who earn no profit from the sale of electricity and heat, the amortization of CHP plants cannot be employed. Therefore, the amortization time for the extra investment, which a CHP plant needs, compared to a conventional heating system, is calculated.

All operating and fuel costs for the CHP plant are assessed as disbursements. All operating and fuel costs for the comparable heating system, the values of power generation (avoided electricity purchases, plus revenue from the power supply) are considered as deposits, and tax credit or debits may need to be taken into account. The difference between the payments and deposits will be accounted for annually and discounted to time zero. The values are cumulative and the dynamic payback period is reached when the cumulative net present values are equal to the added investment of the CHP plant. The smaller the payback period, the smaller is the risk of the investment. If the payback period exceeds the life of the CHP, the plant is not economical. For CHP units in residential buildings payback periods that lie within their lifetime and less, or up to 10 years are quite acceptable. For industrial or commercial combined heat and power applications, which follow the business principle of making a profit, shorter payback periods are required.

CHAPTER III

BUILDING LOAD EVALUATION

The heating and cooling loads of a building to maintain a comfortable room temperature is affected by various factors. These factors are: the solar angles and weather conditions, which are defined by the location, the building with its footprint and insulation materials, as well as the ventilation and infiltration factors. Determination of the cooling load requires additional information about the heat gain by occupants, computers or other appliances. Based on this information the heat can be calculated based on the following equations [10]. The total heat capacity of the building is calculated by the sum of the single heat fluxes.

Heating:

Heat transfer through roofs, ceiling, walls and floors: $Q=U\cdot A\cdot(T_i-T_o)$

Heat Transfer through floors below grade: $Q=U\cdot A\cdot(T_i-T_g)$

Heat Transfer through floors around the grade: $Q=U\cdot P\cdot(T_i-T_o)$

Heat Transfer through ventilation and infiltration $Q_s=1.1\cdot(\mathrm{cfm})\cdot(T_o-T_i)$

$Q_L=4840\cdot(w_o-w_i)$

Cooling:

Heat transfer through roofs, ceiling, walls, and windows: $Q=U\cdot A\cdot CLTD$

Heat transfer through windows (solar): $Q=A\cdot SC\cdot SHGF\cdot CLF$

Heat Transfer through people: $Q_s=No\cdot HG_s\cdot CLF$

$Q_L = No \cdot HG_L$

Heat Transfer through lights: $Q = 1.2 \cdot P_L \cdot CLF$

Heat Transfer through appliance: $Q_s = HG_S \cdot CLF$

$Q_L = HG_L$

Heat Transfer through ventilation and infiltration: $Q_s = 1.1 \cdot \dot{V} \cdot (T_o - T_i)$

$Q_L = 4840 \cdot \dot{V} \cdot (w_o - w_i)$

These heat fluxes are changing with time and thus the thermal behavior of the building changes with time. Generally, heating and cooling demand is calculated on an hourly base over the year. Thus this changes on a daily basis and seasonal changes are taken into account. From the integration of the hourly heat output, this is calculated from the balance of heat fluxes between 0:00 to 24:00 hours, the daily heating or cooling requirements are given. For calculation of the current room temperature T_i, the room temperature computed in the previous step is used, continuously for the next steps. The planner determines the intended room temperature T_{set}. If the measured room temperature is higher or lower, cooling or heating, is required.

The outdoor temperature, the daily solar gains and internal gains from people and equipment, such as TV, computer etc., are considered under the same assumptions as mentioned above. Due to varying heating and cooling loads, the load distribution becomes a function of time. The transfer function method considers the change of the stored thermal energy by following the three assumptions: Discrete time steps, linearity, and causality. This results into the following equation:

$$y(t) = -\left(a_1 \cdot y_{t-1\Delta t} + a_2 \cdot y_{t-2\Delta t} + \ldots + a_n \cdot y_{t-n\Delta t}\right) + \left(b_0 \cdot u_t + b_1 \cdot u_{t-1\Delta t} + \ldots + b_m \cdot u_{t-m\Delta t}\right)$$ [10]

Simplifying the above equation, all the different influence factors are combined in the variable C. Because this transient calculation results in an inhomogeneous linear differential equation of 1st order.

$$Q_{total}=C\cdot T_{average}$$

$$\frac{dQ_{total}}{dt}=\frac{d(C\cdot T_{average})}{dt}$$

CHAPTER IV

COMPONENTS OF CHP

The following chapters will introduce the basics of the CHP technologies, the usable primary fuel, efficiency factors, advantages and challenges.

Fuels

This chapter gives a brief overview of the potential fuels for CHP systems. The applicability for a particular technology is given in the according chapter for the prime movers, where the technologies are described in detail. The choice of fuel has a major influence on CHP systems. On the one hand, fuel cost can be controlled; however, it is important to understand that fluctuation on the market energy price can lead to misleading results in the economic analysis. On the other hand, the environmental impact can be reduced by using less polluting fuels such as biomass and natural gas. Moellersten et al. [29] investigated the potential of carbon dioxide and cost of carbon dioxide reduction. Their results show that CHP is one of the most cost-effective technologies having a large potential for carbon dioxide reduction. The heating value of the fuel indicates how energy dense the fuel is, which directly influences efficiency of the CHP systems. Two different measurements of the heating value exist:

1. Higher Heating Value (HHV)
2. Lower Heating Value (LHV)

Table 2 Heating Values of common Fuels [50]

Fuel	**HHV [MJ/kg]**	**LHV [MJ/kg]**
Hydrogen	141.8	121
Methane	55.5	50
Ethane	51.9	47.8
Propane	50.35	46.35
Butane	49.5	45.75
Pentane		45.35
Gasoline	47.3	44.4
Paraffin	46	41.5
Kerosene	46.2	43
Diesel	44.8	43.4
Coal (Anthracite)	27	
Coal (Lignite)	15	
Wood (MAF)	21.7	
Peat (damp)	6	
Peat (dry)	15	
Methanol	22.7	
Ethanol	29.7	
Propanol	33.6	
Acetylene	49.9	
Benzene	41.8	
Ammonia	22.5	
Hydrazine	19.4	
Hexamine	30	
Carbon	32.8	

The heating value of any fuel is the energy released per unit mass when the fuel is completely burned. The heating value of a fuel depends on the state of water molecules in the final combustion products. The higher heating value refers to a condition in which the water condenses out of the combustion products. Because of this condensation, both sensible and latent heat affect the heating value. The lower heating value, on the other hand, refers to the condition in which water in the final combustion products remains as vapor (or steam); i.e. the steam is not condensed into liquid water and thus the latent heat is not accounted for. In Table 2 higher and lower heating values of some common fuels are given.

Generally, fuels can be defined in two groups: fossil fuels and biomass fuels. It is common in most applications to use fossil fuels, especially natural gas. This also applies to innovative technologies, e.g. the Stirling engine. Renewable energy sources are already widely used for CHP engines in the form of liquid and gaseous fuels. In addition, there are promising developments for the use solid biomass fuels for Stirling engines and steam engines, because their combustion process takes place outside the engine.

Fossil fuels are made by natural processes from buried dead organisms. They do not belong to the renewable energies, because it takes millions of years to form them. For internal combustion the following fossil fuel types are used: natural gas, petroleum gas, gasoline and diesel. Natural gas is the most common gas used for combustion, because of the cheap price and good availability. Refined petroleum gas, along with propane or butane, has a higher heating value than natural gas, but is not as cheap.

Biomass fuel can be produced in relatively short time and from a variety of products, such as: wood waste, crop residues, energy crops, manure biogas, landfill gas, wastewater treatment biogas, and food processing waste. Before biomass is usable as a fuel, it must be processed by direct-fired and gasification systems. In direct-fired burners, biomass fuel burns and produces high pressure steam or hot water. Biomass gasification systems convert solid biomass into solid waste and a flammable gas. This gas is also called synthesis gas or syngas, which is further used for the combustion process.

For the environmental benefit, a detailed investigation of biofuels is inevitable, because not all biofuel are carbon neutral. Some kinds of agricultural feedstock, like soybeans or corn, are particularly far from being carbon-neutral. Both are fertilizer intensive, which increases the greenhouse gas of the produced biofuels. Their production also includes drying process which uses large amounts of energy derived from fossil fuels. Further, compounding of the biofuels ultimately produces more emissions and pushing the fuels farther away from carbon neutrality. However, some other biofuels have the potential to become carbon-neutral in the future. Plants from canola, algae, or sugarcane sequester. If the released carbon dioxide as feedstock in biofuels equals the amount they sequestered as crops, then they can be considered carbon-neutral. The supply and distribution of biomass or biofuel to the consumer must be also taken into account. The emission evaluation is affected by the pollutants which result from transport.

A second interesting aspect for biofuel in CHP application can be the economic calculation. Since biofuels are in general more expensive than natural gas it does not seem to be advantageous on the first glace. However, the government provides special incentives for biofuel, as it is part of the renewable energies, which can be applied by the investor.

Prime Movers

CHP systems consist of a number of individual components: prime movers/ heat engines, generators, heat recovery, and electrical interconnection. The prime mover typically identifies the CHP system. Four different technologies can be characterized: steam turbines, gas turbines, reciprocating engines, and fuel cells.

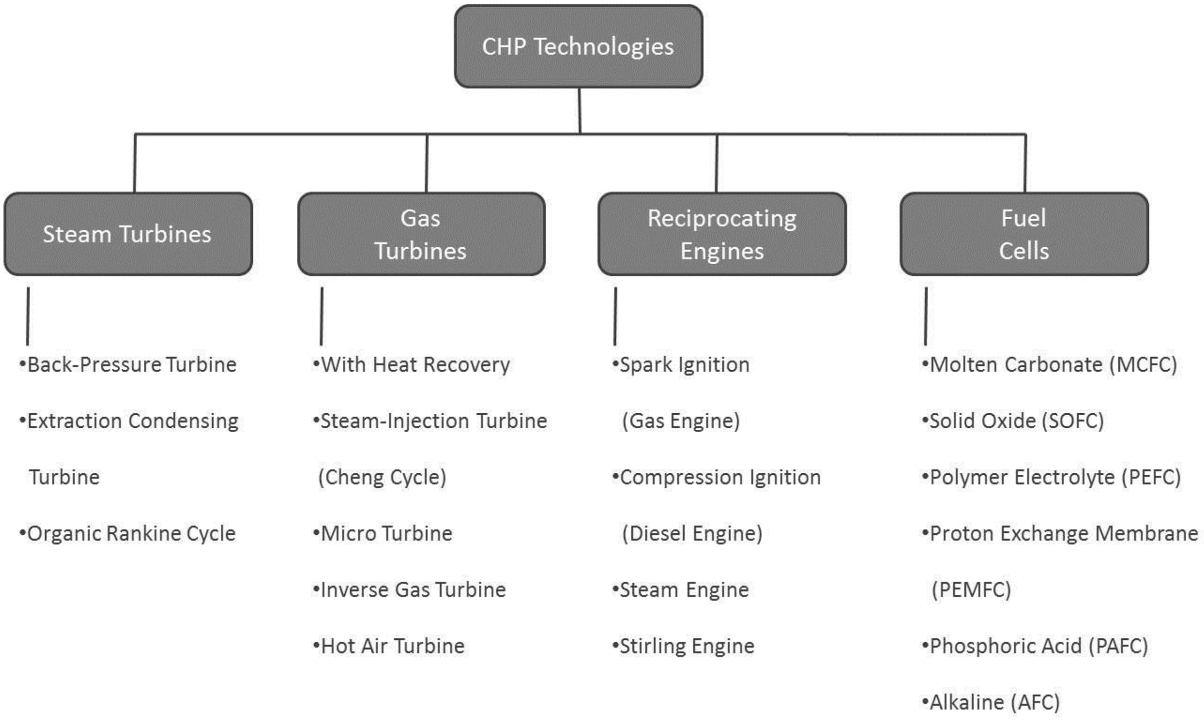


Figure 6 Overview CHP Technologies

Each technology is divided into different versions. In this paper, back pressure turbines, extraction condensing turbines, and the Organic Rankine Cycle (ORC) are described in the area of steam turbines. In the area of gas turbines: heat recovery turbines, steam-injection turbines, micro turbines, inverse gas turbines and hot air turbines are available, while the last two technologies are not further mentioned. Furthermore, reciprocating engines do include spark and compression ignition technologies, steam engines and Stirling engines. The fuel cell has a special status, because it is not based on direct combustion unlike the other CHP technologies. All technologies are described in detail in the next chapters. Depending on the technology the appropriate fuel source can be chosen. Most CHP plants are capable of using a variety of fuels. Details can be found in the corresponding chapters. Further, for each technology a market survey was done and lists for common manufacturers are displayed in Appendix A. An overview Table of all the characteristics of these technologies was established and can be found at the end of this chapter.

Steam Turbines

Steam turbines are one of the oldest engine technologies. The process is based on the Rankine Cycle, which ideally consists of constant pressure heat addition in a boiler, isentropic expansion in the turbine, constant pressure heat rejection and isentropic compression in the pump [6], as shown in Figure 7. The main purpose of a steam turbine system is to produce heat by combustion in the boiler. The generated high pressure, high temperature steam is used to power a turbine and to generate electricity. This is unique for CHP systems, because all other technologies are designed to generate electricity, while heat is the byproduct.

Two different types of steam turbines are used for CHP systems: non-condensing or back pressure turbines and extraction turbines. Back pressure turbines operate on the principle described on the left side of Figure 7. The entire steam flow is used for power generation and the remaining amount of energy is extracted in the condenser. The applications are perfect for a constant heat demand. The operating principle of extraction turbines is similar, with the difference that steam extraction for heat generation is not just at the end, but also in the middle Section of the turbine. This has the advantage that the power or heat generation can be adjusted to different demands.

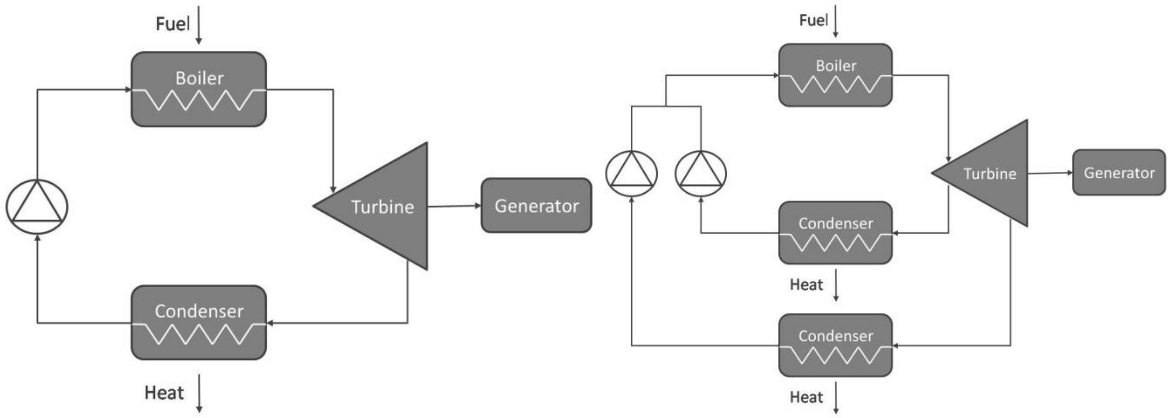


Figure 7 Process for Back-Pressure Steam Turbine (left) and Extraction Steam Turbine (right)

Steam turbines have the advantage that the technology is well known, which results in longevity and reliability. Steam turbine systems have the benefit of external combustion, which means the steam is utilized outside of the power prime mover. Thus, flexibility arises as to choice of fuel, including fossil fuels such as coal, oil, or natural gas, as well as biomass fuels like wood or waste products [46]. The choice of fuel only depends on the selected boiler.

In addition, the power-to-heat ratio can be varied using extraction steam turbines. This makes it possible to meet more than one site heat grade requirement. Compared to other technologies, and because electricity is a byproduct of heat generation, this power-to-heat ratio is relatively low. Also, reliant on the fuel choice are the emissions. The biggest disadvantage of steam turbines is the slow start-up time of the system, due to the design of the turbine. It also has poor part-load behavior, which makes it more suitable for constant heat demand rather than variable demand. There is a broad field of application for middle size about 100 kW to higher demands of 250 MW [23]. In this size range steam turbines are mostly found in industrial applications. The capital cost range is about $800 - $1000/kW. Since heat generation is the main purpose of steam turbines, heat at high thermal quality can be generated. This can also be seen in the efficiency of steam turbines, the thermal efficiency is between 50%– 65%, and the electrical efficiency is around 10%– 20%. Further information is described in Table 4. [43]

A more emerging version of the steam turbine cycle is the Organic Rankine Cycle, also called the ORC process. The main difference to the steam turbine cycle is that an organic working fluid is used instead of water. Examples for such organic fluids are silicone or hydrocarbons like isopentane. The advantage of organic working fluids is the ability to recover heat from lower temperature sources, because the ebullition temperature is lower than water. But, it should be noted, that the low temperatures restrict the heat application. To slow the aging process, which occurs with increasing temperatures, a loop with thermo oil as the working medium is interposed, as shown in Figure 8. ORC is often combined with other renewable energy sources such as geothermal or solar collectors [11] with module ranges between 200 kW and 1500 kW available.

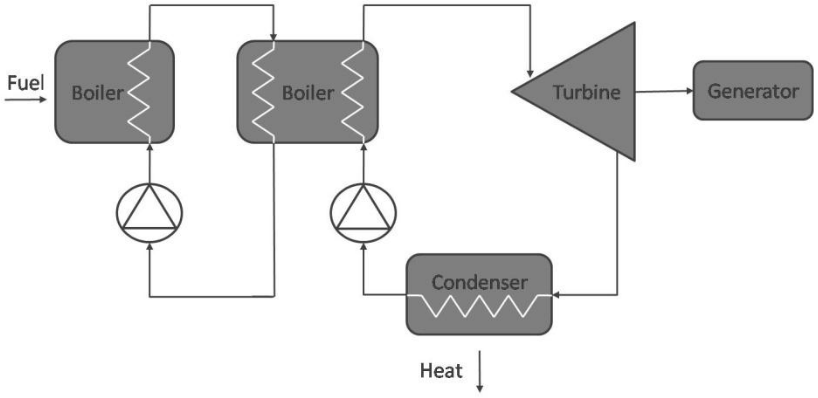


Figure 8 Organic Rankine Cycle

Gas Turbines

The functioning of the gas turbine is based on the Brayton cycle, which describes the ideal cycle for gas turbines. Like the Rankine cycle it consists, of constant pressure heat addition in a boiler, isentropic expansion in the turbine, constant pressure heat rejection and isentropic compression in the pump [6]. Ambient air is drawn into the compressor and then fed into the combustion chamber. There, a combustion reaction takes place by adding fuel. The flue gas is expanded in a turbine, which drives the compressor and the generator for electricity production. The hot exhaust gas exiting from the turbine passes through a heat exchanger, where heat transfer to another medium, usually water, takes place. Afterwards the gas gets exhausted to the environment. In Figure 9, a typical process is shown. In the process shown on the left side, the total amount of heat is used for heat supply. This application is only useful for a constant heat demand. Another application would be steam injection gas turbines. A part of the generated steam is passed back into the combustion chamber and gas turbine and allows the system to adjust to the heat and power demand.

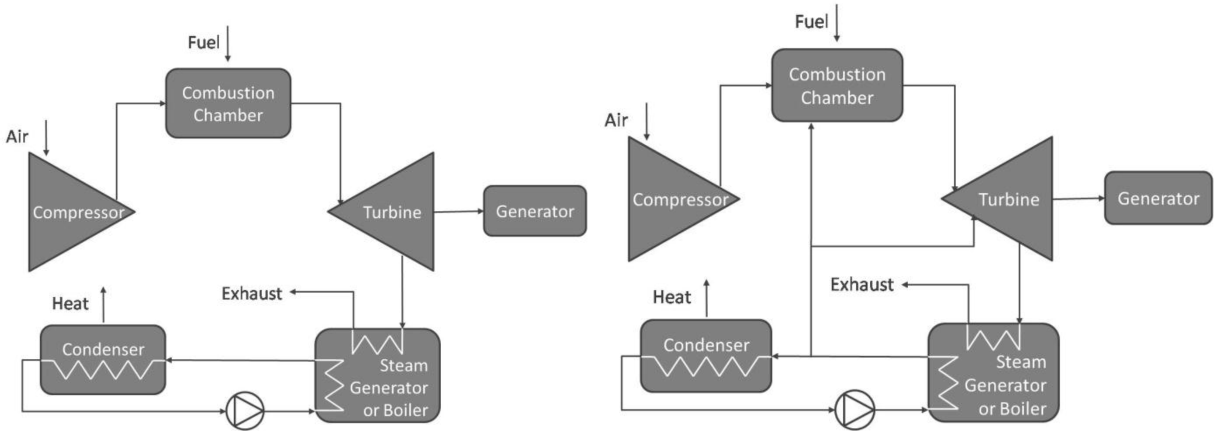


Figure 9 Simple Gas Turbine Process (left), Steam injected Gas Turbine Process (right)

Gas turbines are a well-known and reliable technology with a low cost for power generation. They are available on the market for applications from 250 kW to 520 MW electric power, a compression ratio of 1:16, and reach temperatures up to 1100 °F. Consequently, high temperature heat at a high grade is available, which offers a lot of application possibilities. Even with these high temperatures no cooling equipment is required since excess heat is exhausted to the environment. An issue with gas turbines is the outside air conditions. With increasing air temperatures, the density of the air will decrease, which results in a higher mass flow rate and higher compression rate. Thus, power output and efficiency will decrease. A solution is aeroderivative gas turbines, where high pressure gas or in-house gas compressors operate on a compression ratio of 1:30. It makes the system thermally efficient, light weight, but also more expensive and limited in capacity (max. 40 MW). Recupereators, intercoolers, and inlet air cooling are further efficiency enhancement technologies. Recuperators are basically heat exchangers, which use the hot turbine exhaust gases to preheat the compressed inlet air. If the flow rate through the recuperator can be varied, the released process heat can be increased if needed at the expense of electrical efficiency. While gas turbines generally have applications for a constant heat demand, the recuperators are a good possibility to adjust to a variable heat demand. In intercoolers the compressor is divided in two different compression stages and the air gets cooled before it enters the second stage. The required power for the compression is reduced, but the negative side effect is that the decrease in temperature results in higher fuel consumption. Furthermore, gas turbines have a poor electrical efficiency at low loading, but the overall CHP efficiency does generally not decrease so much because a decrease in electrical energy results in a relative increase in heat energy. This aspect could be advantageous for a steam-driven plant. An additional advantage is that the emission values are very low, because of the high temperatures in the combustion chamber.

Micro turbines are basically the small version of a gas turbine. They are available between 30 kW to 250 kW and thus they are used for smaller applications such as restaurants, multi-family homes, or office buildings. An economic life time of up to 80,000 operating hours can be achieved. The maintenance interval, 4000-8000 hours of operation, is generally much longer than those in internal combustion engines [46]. The functionality and the resulting aspects are the same as mentioned above, so only the differences are described next. First of all, due to the smaller components, a light weight system with compact size can be built. Usually recuperators are used to raise the peak temperature due to preheating. Since the power produced is proportional to the inlet temperature and the inlet temperature is limited to material properties, the current technology is limited to 1800 °F and a pressure ratio of 3.5 to 4. Consequently, the compact design limits the electrical efficiency. Multistage axial flow compressors and turbines are implemented to improve efficiency even further. Production of micro turbines is more expensive than regular gas turbines, as shown in Table 4. There, further performance indicators are shown for gas turbines and micro turbines.

Most applications use natural gas or liquefied petroleum gas as the combustion fuel. But renewable gases such as biogas, sewage gas and landfill gas are suitable too, due to the simple construction of a gas turbine.

Reciprocating Engines

Internal combustion engines:

The most widely used technology in regards to CHP systems are internal combustion engines, because they are robust, well-proven and reliable. They are differentiated between spark ignition (Otto cycle) and compression ignition (Diesel cycle). The mechanical parts of both systems are the same; and both cycles consist of isentropic compression, constant volume heat addition, isentropic expansion, and constant-volume heat rejection. The primary difference is how the combustion is induced. Otto engines ignite the pre-mixed fuel-air mixture by a spark plug; Diesel engines compress the air to a high pressure where the temperature is so high that the mixture gets ignited. Dual fuel engines belong to the spark ignition engines, too. These diesel and gas engines require two fuels for their operation; mainly gas as the energy carrier and a small amount of ignition oil (diesel or fuel oil). The ignition of a highly compressed gas-air mixture is performed by injecting a small amount of diesel fuel (4%-10%).

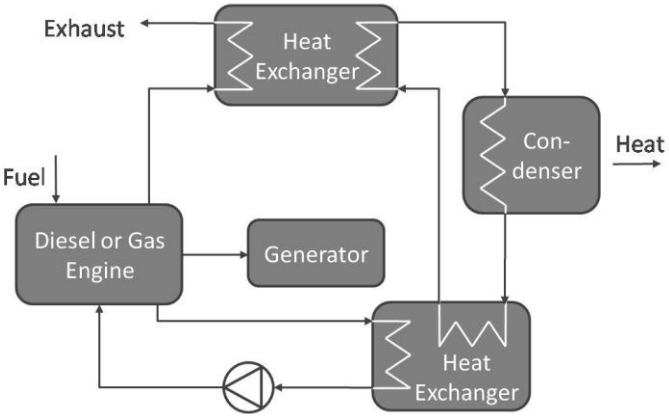


Figure 10 Diesel and Gas Engine Process

A typical process schematic for CHP system is shown in Figure 10. Diesel or gas fuel gets burned inside the engine and rotates the motor shaft. The mechanical shaft work gets converted into electrical power by the generator. Four sources of usable waste heat are available: exhaust gas, engine cooling water, lube oil cooling water, and turbocharger cooling. Variable power adjustment is possible by controlling the fuel input to the engine. An innovation for internal combustion engines in the field of CHP is variable, speed-dependent power modulation. With this technique CHP system performance is independent of seasonal and even daily fluctuations and adaptable to the current thermal and electrical demands. It generates as much energy as needed. Due to the continuous variation to the engine speed, the CHP is always operating with optimum efficiency. The power control throttle valve supplies the motor differing amounts of the fuel-air mixture. But, it will also lead to increased engine wear due to carbon deposits on the valves. The thermal power and gas consumption ratio also decrease advantageously in the partial load range, resulting in significant cost reduction. The use of standard engines from the automotive sector is not fully possible. Those engines have to be modified to ensure reliability in continuous operation.

Generally, reciprocating engines are characterized by good start-up behaviour. They can be started with a minimal amount of power; usually a battery provides enough energy, which makes it perfect for standalone systems. In addition, good part-load behaviour needs to be mentioned. Diesel engines have a small advantage in contrast to Otto engines due to the leaner fuel-air ratio at reduced load. Reciprocating engines generally drive synchronous generators at constant speed to produce steady alternating current power. As the load is reduced, the heat rate of spark ignition engines increases and efficiency decreases. At 50% load the efficiency is approximately 8% to 10% less than under full load conditions contrary to diesel engines whose efficiency stays relatively constant between 50% and 100% load capacity. The electrical efficiency of internal combustion engines is between 25% – 50%, whereas Diesel engines have a little higher efficiency compared to spark ignition engines. Their thermal efficiency is between 60% – 70%. The engine exhaust heat temperature is 850 – 1,200 °F and generates hot water about 200 °F or steam up to 150 psig. The waste heat from the remaining components produces hot water or low pressure steam less than 30 psig. Overall internal combustion engines are a well-known and reliable technology, with a maintenance cycle of 12,000 to 15,000 hours. They are available in a wide range of sizes, 1 kW to 5000 kW. [47]

The main pollutants associated with reciprocating engines are oxides of nitrogen (NO_x), carbon monoxide (CO) and volatile organic compounds (VOC) [9]. As with every engine, emissions are influenced by the fuel source. Diesel engines have relatively high emission pollutants; especially the particulates are an issue. Only Diesel fuel or heavy oil is suitable for a compression ignition engine. For Otto cycles mainly two methods are employed to reduce emission: lean burn/ combustion control and rich burn/ catalytic after-treatment. In general spark ignition engines can be operated with a variety of fuels such as: natural gas, propane, butane, sour gas, gasoline, or biogas such as landfill gas, sewage digester gas, and animal waste digester gas.

Steam engine:

The steam engine is an external combustion engine. For CHP this technology is matured, but it is not implemented in great numbers yet. In Figure 11 the process is shown in a schematic and described below.

A furnace fuel is burned, and the resulting flue gas flows through a steam boiler, which generates the steam. The steam then flows into the steam-engine, pressurizes the piston, and the steam pressure is reduced. The mechanical movement of the piston is then converted into electrical energy in the generator. After leaving the steam engine, the steam is directed into the condenser where the waste heat of condensation can be used to provide heat. The feed water pump brings the water to operating pressure and then into the boiler. The regulator shaft controls the amount of heat entering the piston. The principle corresponds to the control of the steam turbine process, where a piston engine is used instead of a turbine. Power production is possible from 20 kW upwards, which allows decentralized applications.

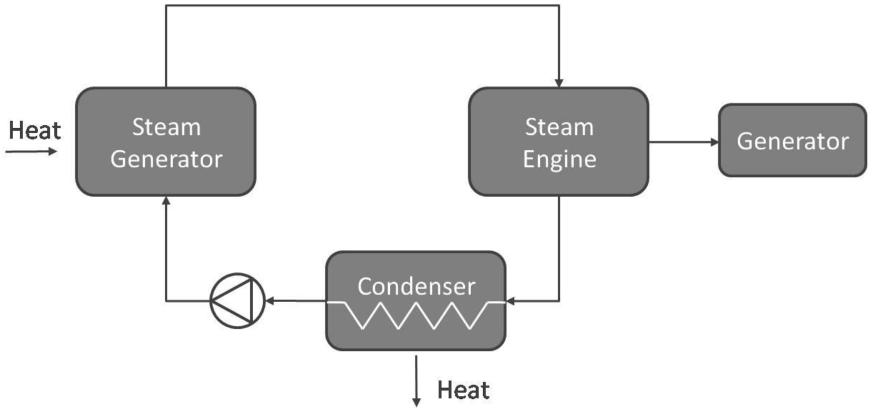


Figure 11 Steam Engine Process

Steam piston engines are characterized by their robustness and durability. They also have very good partial load behavior, and the modular design of the engine allows for very good adaptation to the given operating conditions, and to the required demand for electricity and heat. Steam piston engines can also process steam quality fluctuations of temperature and steam flow better than turbines. These fluctuations can occur in the combustion of biomass due to the differing water content of the fuel. Basically, the operation of the steam engine with each fuel is possible. For this reason, usage of renewable energy sources is particularly interesting. Wood chips, energy crops, wood residues and other residues are used. However, the disadvantage is the low electrical efficiency in the range of 6% to 20%. Furthermore, the steam engine is relatively maintenance-intensive, and it reaches a high noise level (up to 95 dB(A)). An application without very good noise protection is not feasible especially for residential buildings.

Stirling engine

The Stirling engine was an invention of Robert Stirling in 1816. After it was sidelined for years by the internal combustion engine, Stirling engines are gaining back significance in recent years. The reason is the suitability for combined heat and power systems especially for small, decentralized modules.

The Stirling engine is based on external combustion, while the working fluid is trapped inside cylinders and the energy input is done by an external heat source. Figure 12 illustrates the application of the Stirling engine in a CHP system. Generally a fuel is burned in a combustion chamber producing hot gases. These flue gases flow through the boiler heat exchanger and release part of the heat energy to the working gas, e.g. air, nitrogen, helium or hydrogen. The residual heat of the exhaust gas is used via an additional heat exchanger for further heat demand. The cooling of the Stirling engine is done by the return of the heat supply system for a cooler heat exchanger. The movement of the piston creates mechanical shaft work, which is directly coupled to a generator to produce electricity.

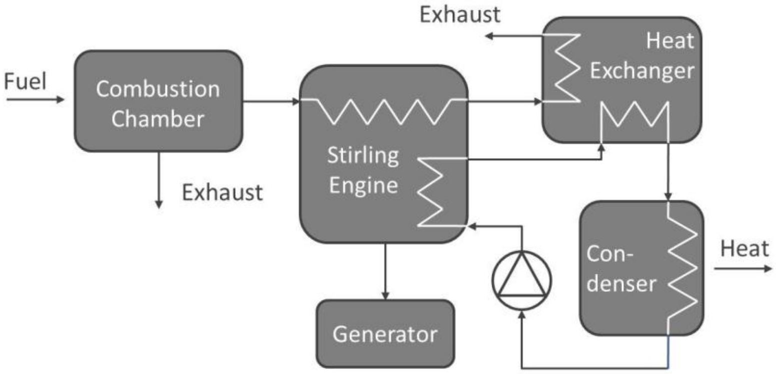


Figure 12 Stirling Engine Process

The thermodynamic cycle is based on isothermal compression, isochore heating, isothermal expansion and isochore cooling. Two types of Stirling engines exist: piston engines and linear free piston engines. First, the piston engine is explained. Inside the Stirling engine the following operating principle occurs, as shown in Figure 13.

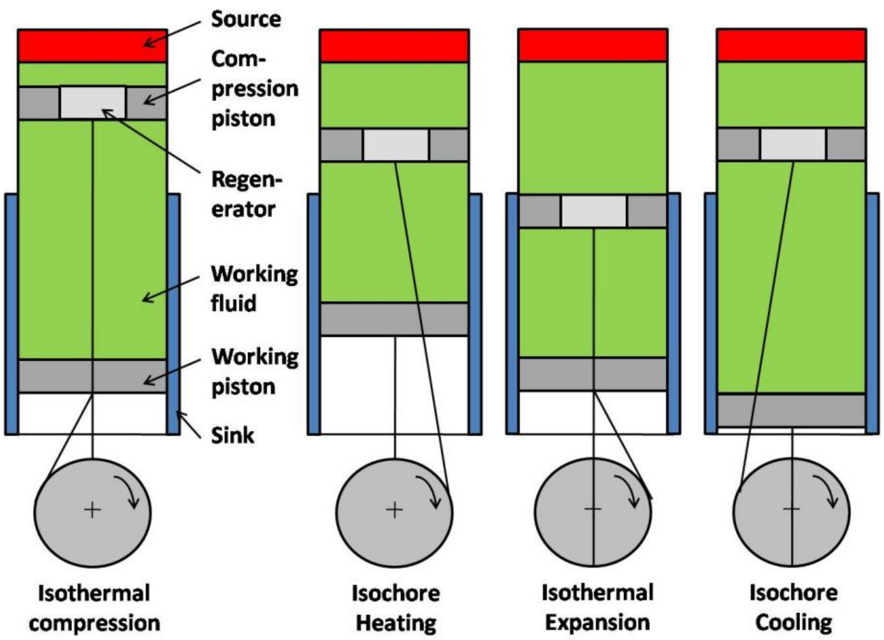


Figure 13 Stirling Engine Process Steps

The Stirling engine makes use of the property of gases to expand strongly when heated and conversely to contract as they cool. Two pistons run in a hermetically sealed cylinder filled with an operating gas. One end of the cylinder is heated by a gas burner while the other is cooled by water from the heating circuit in the building. One of the two pistons – known as the displacer piston – alternately displaces the operating gas from the cold side to the hot side and vice versa. This alternation between heating and cooling produces a pressure difference which moves the second piston - the power piston. The power piston forms part of a generator which converts the piston movement into electricity. Between the two spaces a regenerator is placed. The regenerator is an internal heat exchanger, which removes heat from the hot gas before it enters the cooler. When cold gas flows back, the heat stored in the regenerator can be entered, thereby increasing the efficiency of the engine. Three types of configuration are distinguished according to the configuration: α -, β -, and γ - type. The α type has two or four working pistons. These working pistons are differentiated in expansion and compression and they are located at a 90 °

angle. It has a high power to volume ratio. In a β – type engine, the working and compression pistons are located in one cylinder, as shown in Figure 13. The piston rods are located so that the sequence of the process can be realized. γ –type engines have working and compression pistons, too. However, in contrast to the β – type engine they are located in two different cylinders.

Linear free piston engines work under the same principles as piston engines. The difference comes as the working fluid is transformed and converted into to electrical power, e.g. springs, crankshafts, etc., by the mechanical working piston.

The Stirling engine has several advantages. As mentioned before, it is well suited for small power units up to 100 kW and with its compact design is perfect for smaller decentralized CHP systems. It also features extremely low noise emission and low vibration operation compared to internal combustion engines. Furthermore, the external combustion can be optimized with respect to a large choice of usable fuels and better emissions values than the internal combustion engines. Therefore, the Stirling engine achieves lower emission values. The Stirling engine itself is very easy to maintain and is characterized by low maintenance and repair costs. By the external combustion, there are no carbon deposits on the actual engine, and thus no lubrication problems. The maintenance intervals are assumed to be 5,000-7,000 hours, and are generally higher than those of internal combustion engines. A critical interface, especially in the use of biomass applications, is the contact between flue gas and the boiler heat exchanger, as well as the sealing of the working fluid area. The overall efficiency of the Stirling CHP is in the range of 75% to 95%. The disadvantage is the low electrical efficiency of 15% to 30%, which is a result of the low temperature gradient.

Fuel Cells

Fuel cells were invented by William Grove in 1839. During the last decades research on this technology has been continued, and especially used as an energy source for space applications. It still belongs to the emerging technologies and is not mature yet. In contrast to all other introduced technologies, energy generation in fuel cells is not based on combustion, but on an electrochemical reaction. Five types of fuel cells exist: proton exchange membrane fuel cell (PEMFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC). Table 3 displays a comparison of these different fuel cell technologies. It can be seen, that solid oxide fuel cells have by far the best performance data.

Table 3 Comparison of Fuel Cell Technologies by NREL and [11]

Fuel Cell Type	**PEMFC**	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Membrane	Liquid	Acid	Liquid	Ceramic
Temperature	Low	Medium	Medium	High	Highest
Precious Metals	Yes	No	Yes	No	No
Fuel Flexible	No	No	No	No	Yes
CO_2 Emissions [lbs/MWh]	1200	1200	1200	1000	750
Electrical Efficiency [%]	32	35	37	44	58
Availability	95	95	95	95	99

Each fuel cell system is composed of three primary subsystems: 1) the fuel processor that converts the natural gas into a hydrogen-rich feed stream, 2) the fuel cell stack that generates direct current electricity, and 3) the power conditioner that processes the electric energy into alternating current or regulated direct current [47]. Inside, the fuel cell is divided into anode, cathode, and electrode. In detail the following process takes place: Hydrogen (H_2) is generated in a fuel processor from a hydrocarbon gas, mostly natural gas. The hydrogen (H_2) is fed to the anode and the oxygen (O_2) to the cathode, respectively. The hydrogen gas is electrochemically disassociated into hydrogen (H^+) and free electrons (e^-). The free electrons flow out of the anode through an external circuit to the cathode. This creates a direct current, which gets converted to alternating current in the inverter. The oxygen reacts together with the hydrogen (H^+) and the electrons (e^-) and forms water. The following reactions are taking place [47]:

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall: $2H_2 + O_2 \rightarrow 2H_2O + \text{Energy}$

In order to maintain a sufficient driving force for the ion transfer, the combustion cannot be completed. The remaining fuel will be burned in an afterburner that will produce heat useful for hot water or heating. Figure 14 illustrates the electrochemical process in a typical single cell.

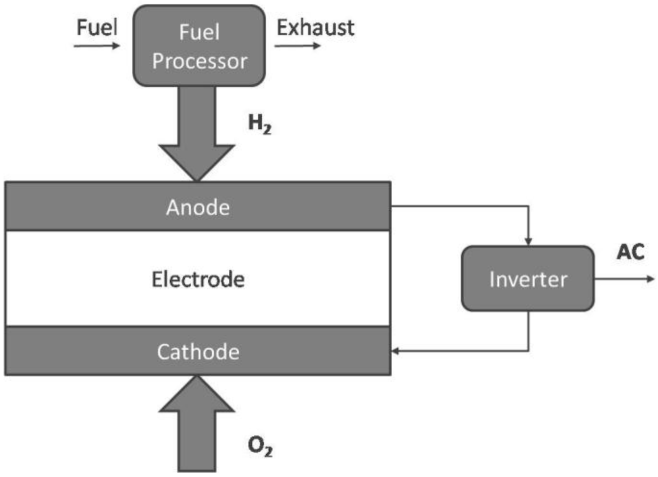


Figure 14 Fuel Cell Process

Fuel cell CHP systems have many advantages including low emissions, low noise level, low maintenance, excellent part-load behavior, and high efficiency [9]. Because of the indirect reaction of hydrogen and oxygen, combustion does not take place. Thus the typical byproducts of the combustion process such as CO or NO_x are not produced. The only source of emission is the fuel processing subsystem. This makes it an extremely low emitter and environmentally friendly process. The hydrogen can be produced from natural gas, propane, coal, or through the electrolysis of water. Maintenance expenditures for fuel cells are low compared to other CHP systems, because they have fewer moving parts, and thus higher availability and reliability can be expected. Fuel stacks need to be replaced between 4 to 8 years, and routine maintenance should take place every 2,000 to 4,000 hours.

The main purpose for a fuel cell is the decentralized generation of power, but the reaction creates high grade heat energy. Together with the exhaust gas out of the fuel processor the heat is used for process heating. Generally a thermal efficiency of 36% can be established and an overall efficiency of 65% to 90%. Application for constant demand ratings are available from 200 to 1,200 kW for commercial and industrial applications, 1 to 10 kW for residential buildings, and 0.5 to 5 kW for portable power systems [47]. It can be seen that a broad range of applications is possible. A further advantage of the fuel cell is that the efficiency is independent of module size, and that they are very efficient even at part-load. Beneficially, the system has also a low noise level (<45 dBA). This makes the fuel cells even for indoor installations is suitable. Thus, fuel cells offer clean, quiet, and efficient power generation.

However, fuel cells have some drawbacks. The technology requires expensive materials. Together with the system's complexity, acquisition costs for fuel cell systems are very high. Another disadvantage is the relatively long start up times, usually a couple of hours.

Overview of CHP Technology Characteristics

The base of this Table is taken from a study done by the following references: [5], [21], [43], [46], [47]. However the list is modified and completed with current manufacturer data shown from the market survey shown in Appendix A.

Table 4 Typical Performance Characteristics by CHP Technology – Part 1 [47]

Technology	**Steam Trubine**	**Gas Trubine**	**Microturbine**
Capacity	100 kW to 250 MW	250 kW to 250 MW	30 kW to 250 kW
Power efficiency (HHV)	15-38%	22-36%	25-40%
Overall efficiency (HHV)	80%	70-80%	70-85%
Typical power to heat ratio	0.1-0.3	0.5-2	0.4-0.7
Part-load	poor	poor	ok
CHP Installed costs ($/kWe)	430-1,100	970-1,300	2,400-3,000
O&M costs ($/kWe)	<0.005	0.004-0.011	0.012-0.025
Availability	near 100%	90-98%	90-98%
Hours to overhauls	>50,000	25,000-50,000	20,000-40,000
Start-up time	1 hr - 1 day	10 min - 1 h	60 s
Fuels	all	natural gas, biogas, propane, oil	natural gas, biogas, propane, oil
Noise	high	moderate	moderate
Uses for thermal output	LP & HP Steam	direct heat, hot water, LP & HP steam, district heating	direct heat, hot water, LP & HP steam
Power Density (kW/m^2)	>100	20-500	5-70
Nox (lb/MMBtU) (not inlcuding SCR)	Gas 0.1-.2 Wood 0.2-.5 Coal 0.3-1.2	0.036-0.05	0.015-0.036
lb/<WhTotalOutput (not including SCR)	Gas 0.4-0.8 Wood 0.9-1.4 Coal 1.2-5.0.	0.17-0.25	0.08-0.20
Advantages	• High overall efficiency/ high temperature/ high quality heat • Any type of fuel may be used • Ability to meet more than one site heat grade requirement • Long working life and high reliability • Power to heat ratio can be varied	• High reliability • Low emissions • High grade heat available • No cooling required • High cost effectivness	• Small number of moving parts • Compact size and light weight • Low emissions • No cooling required
Disadvatages	• Slow start up • Low power to heat ratio	• Require high pressure gas or in-house gas compressor • Poor efficiency at low loading • Output falls as ambient temperature rises	• High costs • Relatively low mechanical efficiency • Limited to lower temperature cogeneration applications

Table 5 Typical Performance Characteristics by CHP Technology – Part 2 [47]

Technology	**Reciprocating Engine**	**Stirling Engine**	**Fuel Cell**
Capacity	0.5 kW to 5MW	2 kW to 1250 kW	0.5 to 2 MW
Power efficiency (HHV)	26-40%	15-30%	30-63%
Overall efficiency (HHV)	70-92%	75-95%	80-90%
Typical power to heat ratio	0.5-1		1-2
Part-load	ok	ok	good
CHP Installed costs ($/kWe)	800-2,200	1,100-2,600	5,000-6,500
O&M costs ($/kWe)	0.009-0.022	0.009-0.013	0.0098-0.0147
Availability	92-97%		>95%
Hours to overhauls	25,000-50,000	>50,000	32,000-64,000
Start-up time	10 s		3 h - 2 days
Fuels	natural gas, biogas, propane, landfill gas, diesel	natural gas, biogas, propane, landfill gas	hydrogen, natural gas, propane
Noise	high	low	low
Uses for thermal output	hot water, LP steam, district heating	hot water, LP steam, district heating	hot water, LP & HP steam
Power Density (kW/m^2)	35-50		5-20
Nox (lb/MMBtU) (not inlcuding SCR)	0.013 rich burn 3-way cat. 0.17 lean burn		0.0025-.0040
lb/<WhTotalOutput (not including SCR)	0.06 rich burn 3-way cat. 0.8 lean burn		0.011-0.016
Advantages	• High power efficiency with part-load operational flexibility • Fast start-up • Relatively low investment cost • Can be used in standalone mode and have good load following capability • Can be overhauled on site with normal operators • Operate on low-pressure gas	• Fuel flexibility • Low emission • Low noise/ vibration level • Good performance at partial load • Relative easy to maintain	• Low emissions • Low noise • High efficiency • Good part load behavior • Low maintenance
Disadvatages	• High maintenance costs • Limited to lower temperature cogeneration applications • Relatively high air emissions • Must be cooled even if recovered heat is not used • High levels of low frequency noise • No high grade heat available	• Low electrical efficiency	• High costs • Low durability • Fuels requiring processing unless pure hydrogen is used • Start-up time

Efficiency of CHP Systems

Energy efficiency η is the ratio of useful energy output over energy input. This basic rule applies also for combined heat and power systems, while the fraction of useful energy consists of power and heat. The remaining energy is lost as low temperature heat within the exhaust gases and as radiation and convention losses from the engine and generator. The calculation of the efficiency is based on the following equations:

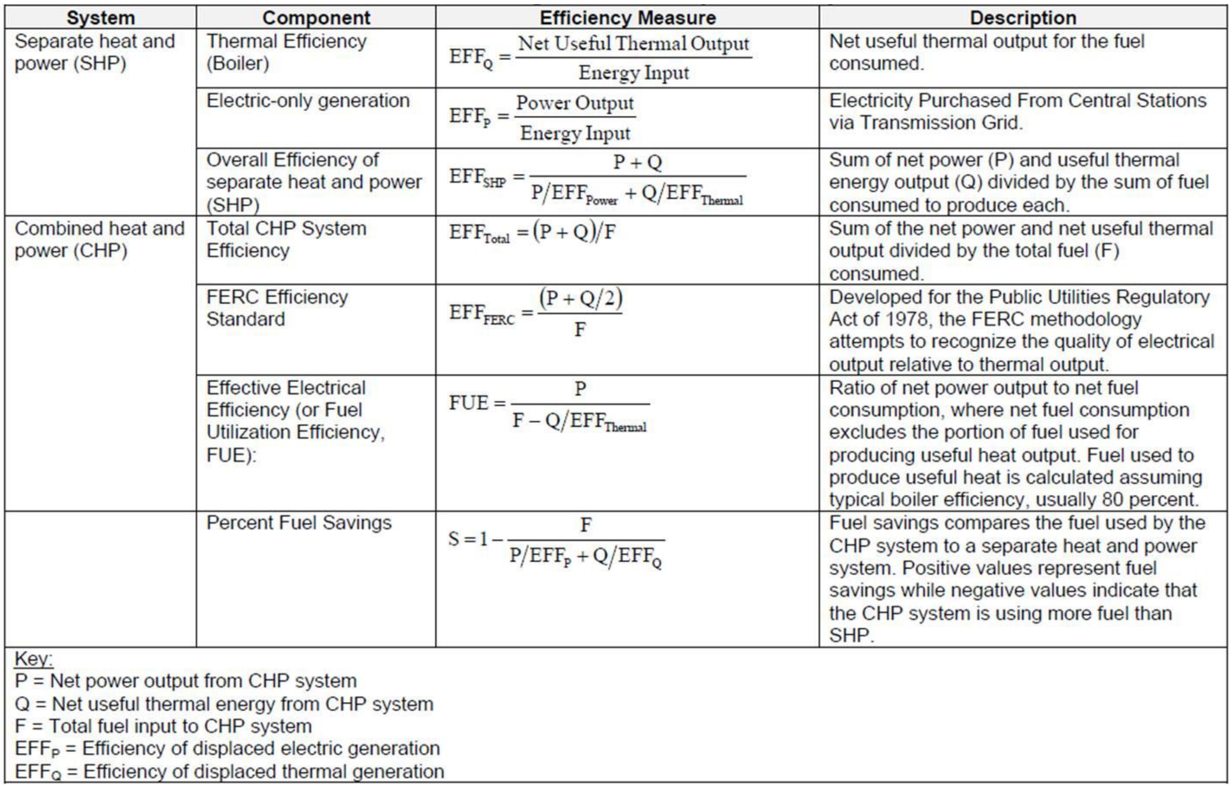
Electrical efficiency $\eta_{el}=\frac{P_{el,\ out}\ (kW)}{P_{fuel,\ in}(kW)}$

Thermal efficiency $\eta_{th}=\frac{P_{th,\ out}\ (kW)}{P_{fuel,\ in}(kW)}$

Overall efficiency $\eta_{t}=\frac{P_{el,out}\ (kW)+P_{th,out}\ (kW)}{P_{fuel,\ in}(kW)}$

The overall efficiency of a CHP system depends on the prime mover, its size, and the temperature at which the recovered heat can be utilized. The overall efficiency is, however, a first law efficiency that does not represent the quality of the electrical and heat production. For CHP systems it is worth considering the exergy efficiency of the system, i.e. the availability or capacity of the system to perform useful work. The exergy efficiency is expressed as the ratio between the exergy delivered by the system and the exergy entering with the fuel. Usually, the quality and value of electric energy is higher relative to the heat output. Further, it is easier to transmit electricity over long distances or convert it into other forms of energy. For this reason, the Public Utilities Regulation Regulatory Policies Act of 1978 (PURPA) introduces the calculation of the efficiency standard Eff_{FERC} [47]. This basic change is that the thermal output only counts half. Another useful measure for a CHP system is the fuel utilization effectiveness (FUE). The FUE describes effective electrical efficiency, where the portion of useful heat is excluded. A third calculation, and by the EPA considered as the most appropriate one, is the percentage of fuel savings [47]. In this calculation the comparison with a separate heat and power system is made. Positive values represent fuel savings while negative values indicate that the CHP system is not appropriate. All calculations are summarized and are shown in Table 6.

Table 6 Measuring the Efficiency of CHP Systems [47]



System	Component	Efficiency Measure	Description
Separate heat and power (SHP)	Thermal Efficiency (Boiler)	$EFF_Q = \frac{\text{Net Useful Thermal Output}}{\text{Energy Input}}$	Net useful thermal output for the fuel consumed.
	Electric-only generation	$EFF_P = \frac{\text{Power Output}}{\text{Energy Input}}$	Electricity Purchased From Central Stations via Transmission Grid.
	Overall Efficiency of separate heat and power (SHP)	$EFF_{SHP} = \frac{P + Q}{P/EFF_{Power} + Q/EFF_{Thermal}}$	Sum of net power (P) and useful thermal energy output (Q) divided by the sum of fuel consumed to produce each.
Combined heat and power (CHP)	Total CHP System Efficiency	$EFF_{Total} = (P + Q)/F$	Sum of the net power and net useful thermal output divided by the total fuel (F) consumed.
	FERC Efficiency Standard	$EFF_{FERC} = \frac{(P + Q/2)}{F}$	Developed for the Public Utilities Regulatory Act of 1978, the FERC methodology attempts to recognize the quality of electrical output relative to thermal output.
	Effective Electrical Efficiency (or Fuel Utilization Efficiency, FUE):	$FUE = \frac{P}{F - Q/EFF_{Thermal}}$	Ratio of net power output to net fuel consumption, where net fuel consumption excludes the portion of fuel used for producing useful heat output. Fuel used to produce useful heat is calculated assuming typical boiler efficiency, usually 80 percent.
	Percent Fuel Savings	$S = 1 - \frac{F}{P/EFF_P + Q/EFF_Q}$	Fuel savings compares the fuel used by the CHP system to a separate heat and power system. Positive values represent fuel savings while negative values indicate that the CHP system is using more fuel than SHP.

Key:
P = Net power output from CHP system
Q = Net useful thermal energy from CHP system
F = Total fuel input to CHP system
EFF_P = Efficiency of displaced electric generation
EFF_Q = Efficiency of displaced thermal generation

Barriers to CHP Technologies

Even though CHP provides many benefits, as described earlier; but it also has certain barriers to face. These barriers come in many forms, and can be categorized as technical, environmental, economical, and knowledge barriers.

Technical Barriers:

One of the technical barriers is the grid interconnection. CHP systems, which are operating parallel to the grid, need a safe and reliable connection to it. The current existing grid is not fully designed for back and forth electricity transactions, and the current lack of standards makes it difficult for grid operators and manufacturers to provide uniform solutions. However, the International Electrical and Electronics Engineers (IEEE) developed a standard for interconnecting distributed resources with electric power systems, which is already adopted by several states [25]. But the process to adjust the grid takes time.

Another technical aspect is that some technologies, e.g. Stirling engines, have not reached fully marketability, yet. Consequently, there are still only a few concrete practical evaluations over their lifetimes, as to their need of maintenance and repair, and thus the efficiency of these units.

Environmental Barriers:

According to the International Energy Agency (IEA) there is still a lack of recognition of CHP in environmental regulations. Most U.S. environmental regulation established emission limits based on heat input (kg/kWh) or exhaust concentration (ppm), in order to account for the efficiency benefits of recovering waste heat or savings due to the eliminated transmission losses. Using output-based calculation standards (kg/kWh of total output) can be a way to recognize the benefits of CHP systems. However, a federal procedure for issuing permits is still missing. [26]

Economic Barriers:

The economic barriers carry the highest potential of improvement for CHP, because the systems are measured, e.g. at their cost. Companies are faced with the question of whether profitable investments in alternative energy supply are reasonable, or an investment in their core business is better than the construction and operation of a CHP plant. The idea that CHP is not necessary to maintain the supply of electricity and heat, but "only" brings energy savings and thus protects the climate, can also have influence on this decision.

First, costly standby and backup charges can come to the operator. Back up rates are intended to allow utilities to recover the cost of developing and maintaining capacity to provide service for generation, transmission, or distribution of capacity. In general, rate structures have a large influence on the economic feasibility of a CHP system. Rising demand charges, as well as rate structures that recover the majority of the cost by fixed service charges, reduce the economic savings potential of CHP [26].

Another issue is tax policy. CHP systems do not fall into a specific tax depreciation category. As a result, the depreciation period can range from 5 to 39 years [26]. This circumstance might make it more difficult for some owners to recover acquisition costs.

A third economic barrier could be that the energy costs on the market effect the economic feasibility of CHP systems. Depending on which fuel the CHP system uses the purchase of this fuel source has to be cheaper than the price for electricity. If the fuel is expensive relative to electricity, it does not make sense to purchase it to produce electricity. In most cases natural gas is used to operate the CHP system. Thus, it should be noted, that the price for natural gas must be cheaper than the price for electricity. In general, a low electricity price, a lack of compensation or surcharges for electricity fed into the grid, and a high fuel cost, are economic barriers for the use of CHP. This especially influences small scale CHP operations.

Another influence factor is especially important for small scale CHP systems: the electrical efficiency decreases with the size of the plant. In return, however, higher investment costs and higher maintenance costs must be paid for smaller plants. This can also present a barrier to the economy for Micro-CHP. Therefore, care should be taken to get the best possible heat adjustment, between demand and generation, especially for smaller systems with self-used electricity.

Knowledge Barrier:

In addition, CHP technology faces organizational and administrative challenges associated with finances, time, and effort (obtaining permits for construction, proposals, negotiating with utility companies, etc.). This can be a major barrier, since the power supply is usually not the core business of companies. However, the DOE provided funding support early in the CHP Challenge and Roadmap years to establish the Midwest CHP Regional Application Center (RAC), based at the University of Illinois – Chicago. The RAC offers CHP technical assistance, training, educational opportunities, and outreach support. Further improvement of education and outreach on CHP is provided by DOE with the assistance of Oak Ridge National Laboratory which supports eighteen education and outreach contracts. [25]

EPA further collaborated with the DOE and other stakeholders by establishing the Combined Heat and Power Partnership (CHPP) in 2001 to support and assist cost-effective CHP projects in the United States. It is a volunteer program with the goal of reducing the environmental impact of power generation by using CHP systems. This partnership works closely with energy users, the CHP industry, state and local governments, and other clean energy stakeholders to facilitate the development of new projects and to promote their environmental and economic benefits [48]. One result of this partnership is the ENERGY STAR CHP Award. The ENERGY STAR CHP Award recognizes highly efficient CHP systems that reduce emissions and use at least 5% less fuel than comparable, state-of-the-art, separate heat and power generation.

CHAPTER V

RESULTS OF CHP APPLICATION FOR A RESIDENTIAL BUILDING

In the second part of this paper, the applicability of a Micro-CHP system for residential buildings in the USA is investigated. In Europe, especially in Germany, the UK and the Netherlands, as well as in Japan, Micro-CHP is already a more or less established technology. But those countries are characterized by a widely available gas network, reasonable long heating seasons, and high electricity prices. In contrast, the U.S. residential building energy concept is still based on a conventional power supply. This analysis will give an idea of the usability for small, decentralized CHP systems. Therefore, a typical single family house (two adults, two children) is modeled to generate load distributions for electricity, hot water, space heating and space cooling.

First a conventional supply system is described. Typical systems in the U.S. are boilers and furnaces, based almost entirely on natural gas, or electricity. The separate heat and power generation is used as a reference calculation. Next, combined heat and power technologies are investigated. Residential buildings have demand smaller than 4 kW_{el}. Due to this limited range only a few technologies are suitable: reciprocating internal combustion engines, fuel cells, and external combustion/ Stirling engines. For this case study one unit is selected for each technology for the calculations.

The calculations of heating and cooling loads are based on TRNSYS; for all further calculation the CHP simulation software BHKW Plan is used. This analysis is focused on site energy consumption, emissions, as well as resulting economics. The effect of different fuel types is not investigated, and only one fuel source is considered to simplify calculations and to make the different systems comparable to each other. Natural gas is chosen, due to the fact that it is cheap, widely available in residential areas, and CHP units are usually designed for it.

Building Loads

The building loads are composed of the heating and cooling loads of the building, the hot water demand, and the electricity demand. These loads arise from the building envelope, the weather, and the people living in the building. Details are described in the next chapters.

Building Description

The heating and cooling loads are mainly influenced by the design of the building and the weather conditions. Northern regions have a higher heating demand and southern regions a higher cooling demand, which influences the building design. The EIA divides the U.S. into four climatic regions, while this study concentrates only on the far north and far south region, taking Chicago, IL and Atlanta, GA as example. The building description is based on different studies in this area [2], [16], as well as ASHREA Guidelines. In Table 7 the dimensions as well as the thermal resistance values of walls, ceiling and floor are described for both buildings. These data are the basics for the TRNSYS model. Additional drawings for the buildings can be found in Appendix B.

Table 7 Building Dimensions and Thermal Resistance

Housing Type			North Region Chicago	South Region Atlanta
Number of Stories			1	1
Foundation Type			Unheated Basement	Slab
Conditioned Floor	Area	[m^2]	114	124
Ceiling	Area	[m^2]	114	124
	R-Value	[m^2 °C/W]	6.7	6.7
Walls	Area	[m^2]	93	98
	R-Value	[m^2 °C/W]	3.3	3.3
Windows	Area	[m^2]	14	15
	U-Factor	[W/m^2 °C]	2.3	3.7
Infiltration	Area	[m^2]	114	124
Foundation	Area	[m^2]	114	124
	Perimeter	[m]	44	46
	R-Value	[m^2 °C/W]	-	2.3
	R-Value	[m^2 °C/W]	-	0.4
	R-Value	[m^2 °C/W]	2.5	-

Weather Data

The weather data considered are based on weather data provided by NREL. The TMY2 (typical meteorological year) database is produced by the U.S. National Renewable Energy Laboratory's (NREL's) Analytic Studies Division under the Resource Assessment Program, which is funded and monitored by the U.S. Department of Energy's Office of Solar Energy Conversion [30]. The data sets include hourly values of solar radiation and meteorological elements for a one year period. For this paper the meteorological data of Atlanta, GA and Chicago, IL are picked as two reference cities for the northern and southern region in the U.S.

Heating and Cooling Load

The heating and cooling loads are determined according to the theory and calculations described in chapter III. However, some simplifications are made for this model. The building is considered as one big room, which is described by one average room temperature. Thus, multi zones are not included, except the unheated basement. Further, the set temperature for heating and cooling is defined at 21 °C/ 25 °C, according to ASHREA Fundamentals [1]. In Table 8 the schedule for the electrical appliances is defined which shall represent the living behavior of an average family.

Table 8 Building Load Schedule

Schedule	From	Until	Value
Computer (230W)	0:00	15:00	off
	15:00	23:00	on
	23:00	0:00	off
Lights ($5W/m^2$)	0:00	5:00	off
	5:00	8:00	on
	8:00	18:00	off
	18:00	23:00	on
	23:00	24:00:00	off
Worklights ($5W/m^2$)	0:00	8:00	off
	8:00	18:00	on
	18:00	24:00:00	off

The simulations, to determine the heating and cooling loads in Atlanta and Chicago, are established with the simulation software TRNSYS. Detailed explanation of the model can be found in Appendix C, and results are shown in Figure 15 and Figure 16.

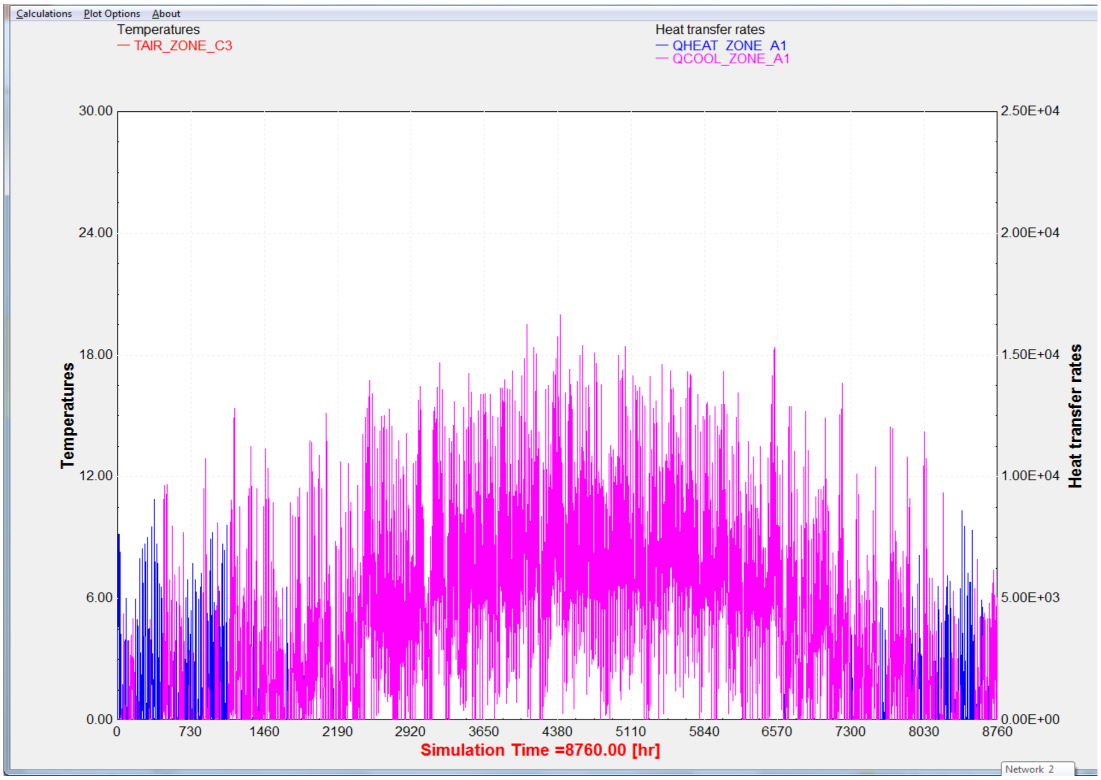


Figure 15 Heating and Cooling Load Atlanta

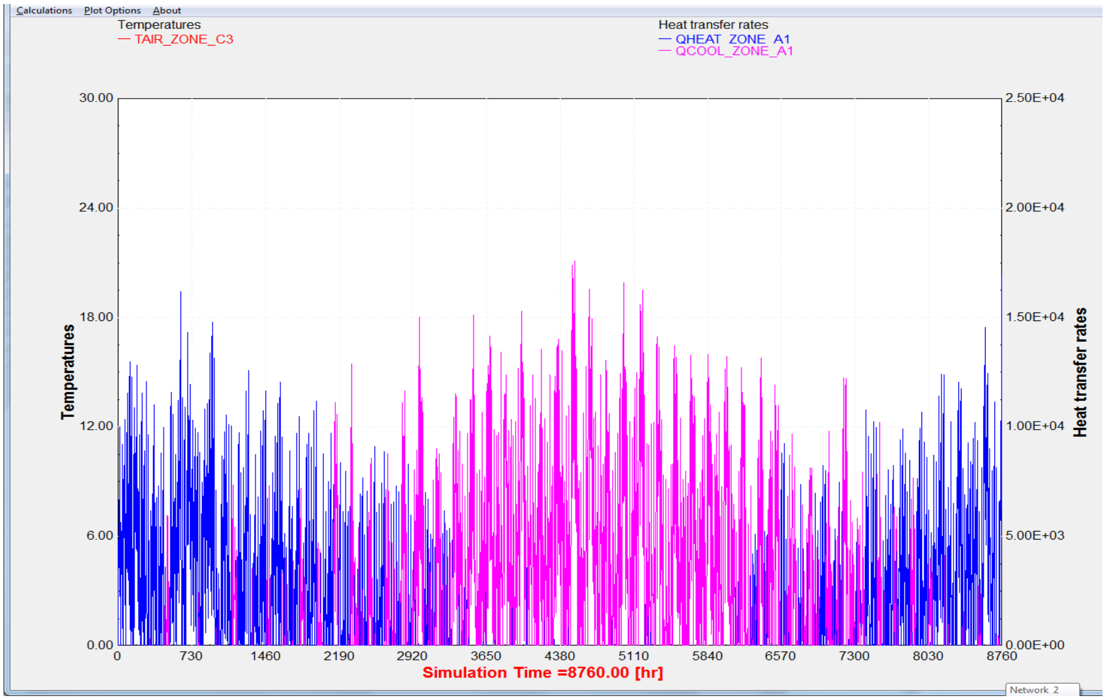


Figure 16 Heating and Cooling Load Chicago

Hot Water

The hot water demand is, after building heating, the second highest consumer of thermal heat. The amount and distribution of the hot water demand is composed of the number of bathrooms, toilets, showers, the number of people who use them, as well as hot water equipment such as dishwashers, and washing machines. Different studies are published presenting the hot water demand in the U.S., e.g. University of Central Florida [15], Department of Energy [40], or Becker and Stogsdill [4]. However, all studies show average values for the U.S. and do not give more precise disclosures for specific cities or regions. For this reason, no difference in consumption is made based on the locality. The usage distribution is developed based on the named literature and is shown in Figure 17.

The second factor for the hot water demand calculation is the temperature requirement. The Pacific Gas and Electric Company provides monthly ground water temperatures for different climate zones [15]. This analysis is based on the values shown in Table 9. The water supply temperature is set to 60 °C, as recommended by ASHREA [1].

Table 9 Monthly Average Supply Temperatures in [°C] [15]

	January	February	March	April	May	June
Atlanta, GA	15.6	14.9	14.8	15.1	16.4	17.7
Chicago, IL	15.1	14.5	14.4	14.7	15.8	16.9

	July	August	September	October	November	December
Atlanta, GA	18.9	19.6	19.7	19.1	17.9	16.7
Chicago, IL	17.8	18.4	18.4	17.9	17.1	16.0

Based on the temperature and usage data the energy demand can be calculated based on the following equation:

$$Q=\dot{m}\cdot c_p\cdot(T_s-T_i)$$

where c_p is the specific heat of water, which is 4.183 [kJ/kgK]

The resulting distribution of the hot water demand, for Atlanta as well as for Chicago, is illustrated in Figure 17.

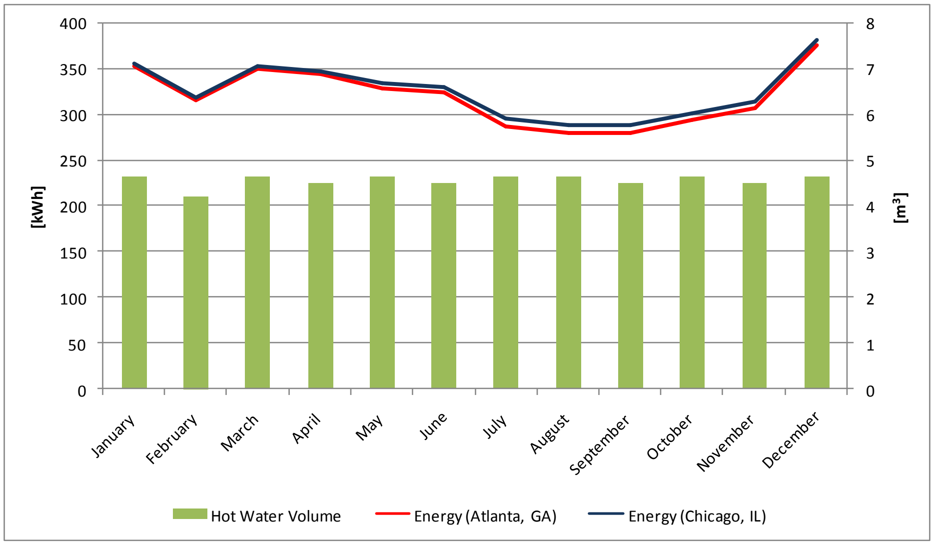


Figure 17 Hot Water Demand

Electricity Demand

The electricity demand is composed of lighting, appliances, and miscellaneous equipment, while appliances and miscellaneous parts consist of different users, such as dishwashers, clothes washers, driers, home entertainment equipment, kitchen supplies, home office equipment, etc. The data used in this paper are based on a study by the Department of Energy [40] and a study of the Lawrence Berkeley Laboratory by the University of California [16]. Summation of this study results in the distribution shown in Figure 18. The load change on an hourly base over one day is taken into account, but for simplification purposes the load change due to the season is neglected.

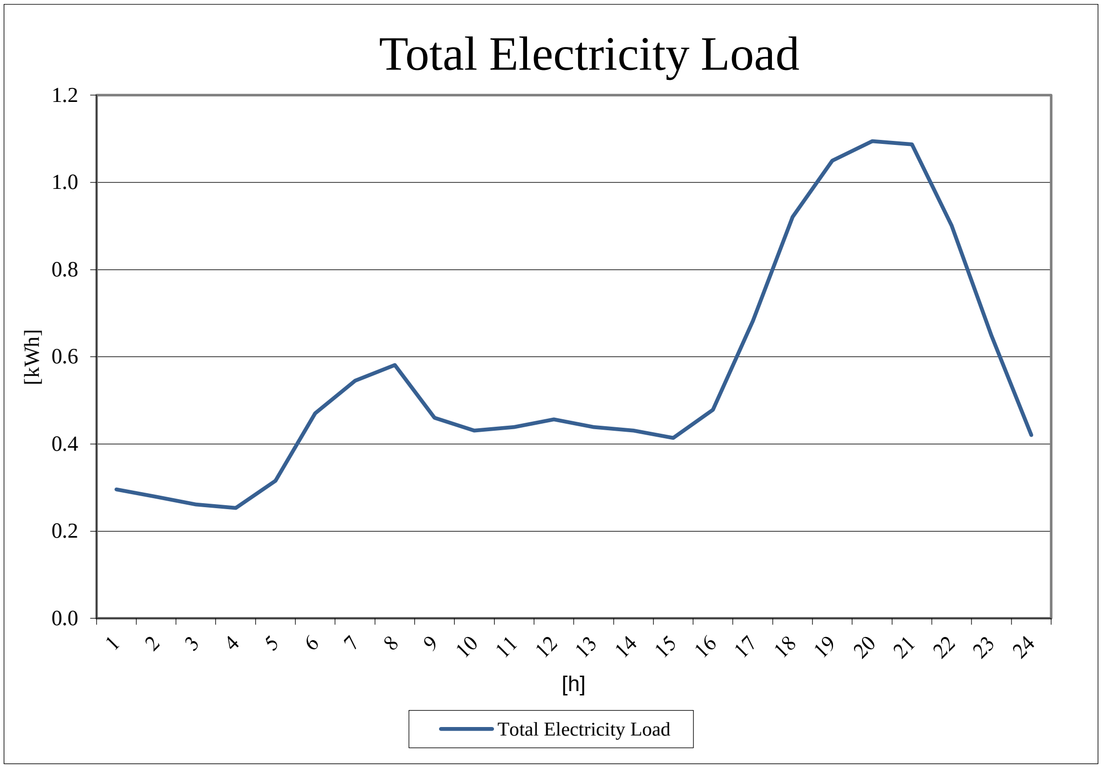


Figure 18 Electricity Demand over 24h

Another significant proportion of electricity load is consumed by air conditioning systems. The cooling load, calculated and shown in the Section “Heating and Cooling Load”, is added to daily electricity demand shown in Figure 18. There, an efficiency of 20% [27] for the air conditioning unit is assumed, and results in the following yearly electricity consumption.

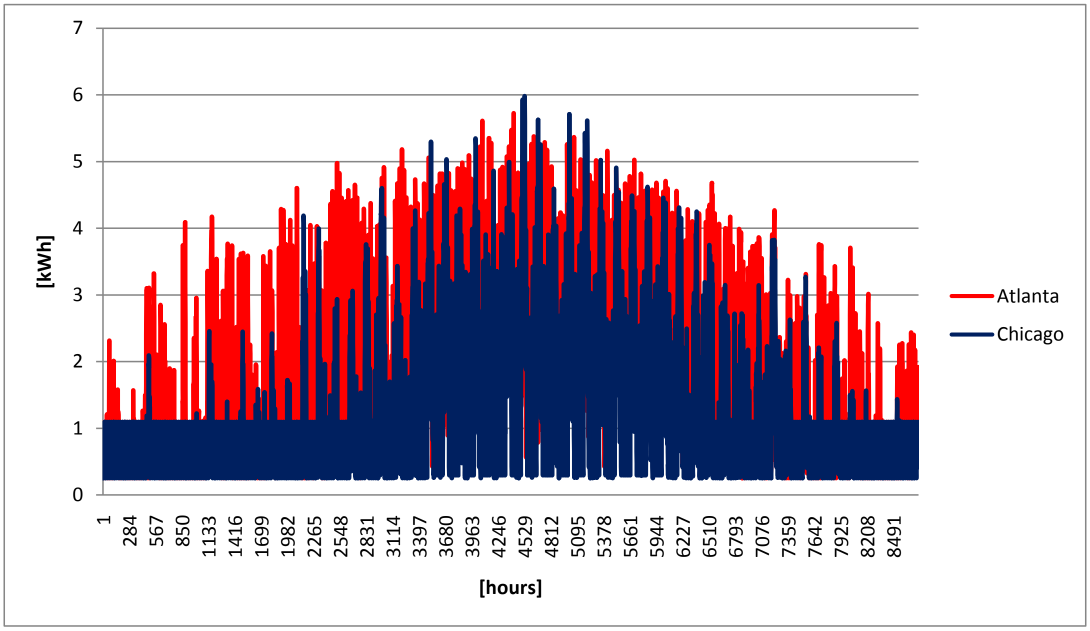


Figure 19 Annual Electricity Consumption for Atlanta and Chicago

Energy Requirements for Residential Buildings

The load distribution affects the equipment design. Especially the heating load will have an effect on the thermal storage system and the CHP system, since the usage of heat is the key factor for CHP systems. By counting the different heat and electricity demands together, the annual demand is established, as shown in Table 10. The heating demand in Chicago is significantly higher than in Atlanta, which is a result of the colder and longer winters in Chicago. Conversely, for the electrical demand, Atlanta's power demand is 14.1 MWh/a higher than Chicago's, due to the hot summers, where temperatures are cooled down by electric air conditioners.

Table 10 Total Heat and Power Demand

		Atlanta	Chicago
Heat Demand	[MWh/a]	4.7	7.5
Power Demand	[MWh/a]	14.1	10

Supply Systems

The most common Micro-CHP systems for residential applications are internal combustion engines, Stirling engines, and fuel cells. They can be built in small scale, and can operate silently. For this reason, these three technologies are investigated in this case study. Additionally, a conventional system with separate heat and power generation is described for comparison. It needs to be noted that for all systems only natural gas is considered as fuel source. There are two reasons for this: First natural gas is a cheap and easily available fuel source, and most CHP system can be operated with it. Further, the capability of Micro-CHP for residential buildings is the focus of this case study; thus the influence of the fuel source is kept fixed.

Separate Seat and Power System

Conventional heat and power is provided by separate systems. Today, most homes built in the United States use a forced air system to provide cooling. For further calculations, a Lennox HVAC system with 20% efficiency is considered. For heating and hot water generation a natural gas boiler from Viessmann with 94% efficiency is used. A sketch of a typical separate heat and power supply system is shown in Figure 20. All involved heat processes are shown in red, cooling in blue, and electricity in yellow.

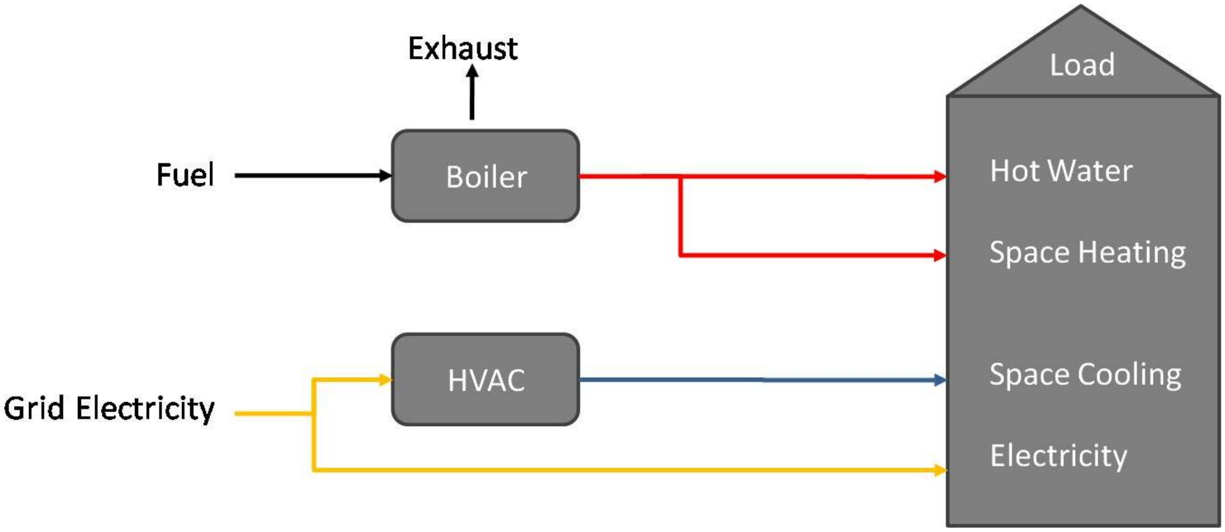


Figure 20 Separate Heat and Power Supply

For the separate supply system, the electricity is brought from the grid and produced by a central power plant. The amount of primary energy needed to produce the electricity depends on the technology used. The approach recommended by Sweester [36], Hedman and Hampson [19] using EPAs eGRID values could not be followed because eGRID provides values for CO_2, CH_4, and N_2O, whereas the BHKW Plan simulation software requires CO_2, CO, SO_2, NO_x and dust values. According to the IEA, coal powered plants deliver the majority of power. Thus, the IEA values are taken as a baseline to obtain emissions. Detailed emission data are taken from the CEC report [28]. Further, 7% transmission losses by the grid are taken into account [21].

Table 11 Average U.S. Power Plant Emissions

Efficiency		[%]	39
Emission	CO_2	[mg/kWh]	893,000
	SO_2	[mg/kWh]	3,790
	NO_X	[mg/kWh]	1,660
	CO	[mg/kWh]	230

Integration of Combined Heat and Power

The implementation of a CHP system is shown in Figure 21. Since Micro-CHP systems run most efficiently under constant conditions, the system has to run for a certain amount of time. To adjust to the varying electricity demand, a battery is sometimes placed as a buffer between the building load and the electric output of the CHP system. With those batteries stand-alone systems are possible. Batteries, however, are still very expensive, and are not required as long as the system is not placed in a very isolated area. In general a direct connection to the grid makes more sense, and thus the battery option is not considered in this case study. For a varying heating load, a thermal tank is integrated into the supply system. In general, those tanks are already included in the CHP unit, like in the chosen units for this study. In addition, an auxiliary boiler/ peak boiler is employed in case the demand exceeds the heat generation or the CHP fails. As described in the Section “Principles of Combined Heat and Power”, CHP systems can be operated in power or heat-oriented mode. In this case study only the heat-oriented operation is considered, since for residential buildings it is easier to adjust the electricity, and focus on heat generation. Thus, only the heat-oriented interpretation guarantees the highest possible utilization of the fuel, and with that the technically highest achievable overall efficiency. Space cooling is still provided by an electric air conditioning system with 20% efficiency. Absorption chillers are not applicable for this size, because the acquisition costs are too high. Thus, there are only a few manufacturers in the market.

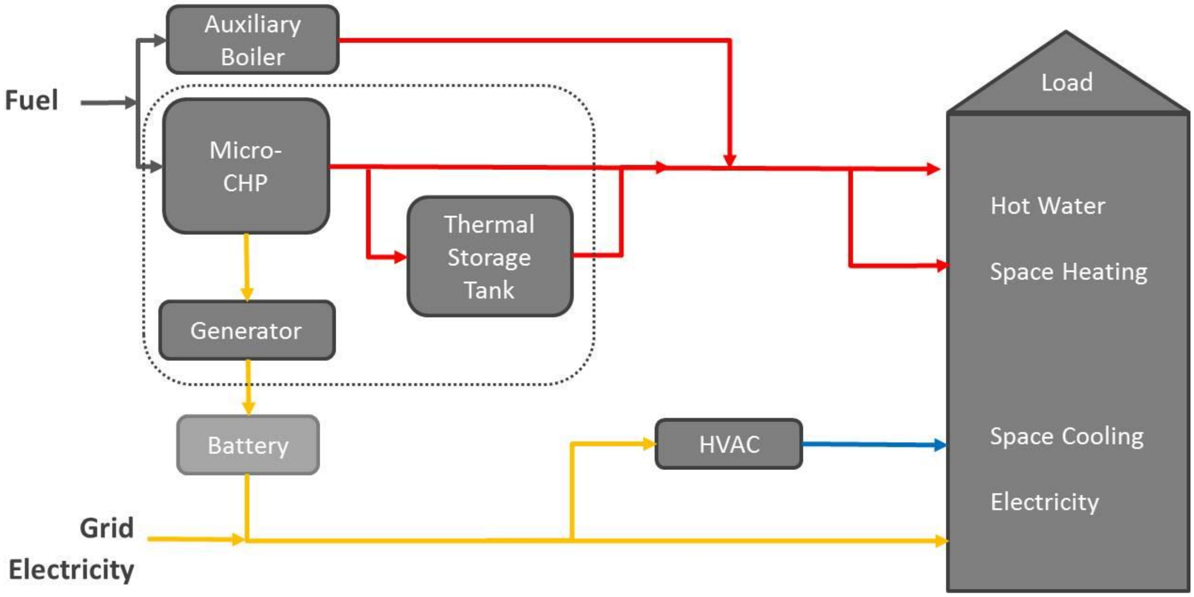


Figure 21 CHP integrated System

As mentioned, three different CHP systems are considered for this case study. Usually, the selected CHP systems are designed for approximately 30% of the total heat demand. In this case study, it was not possible to find such a system at that size on the market. Thus, the smallest CHP systems available on the market have been chosen. As a spark ignition engine, the Otto Engine from the German manufacturer Vaillant is chosen. Vaillant co-operates with the car manufacturer, Honda, and uses their engines for the CHP unit. Their system is applicable from 15,000 kWh/a, and achieves 1 kW_{el} electrical power and 2.5 kW_{th} thermal power. For Stirling engines, the DACHS system from Senertec was picked, with 1 kW_{el} electrical power and 6.1 kW_{th} thermal output, which is the highest of the three comparable examples. As a fuel cell application, the smallest available SOFC system from BlueGen was chosen, because of the small load of a residential building. Compared to the two reciprocating engines, the fuel cell produces 2 kW_{el} of electricity and 1 kW_{th} is the thermal output. All units have a thermal storage tank of 1 m^3, which equates to 23 kWh of thermal storage capacity. For all units the minimum operation set point is 50% of the design value of the CHP system. If the demand is below that value, the system will be shut down, because the system will not operate efficiently enough. The size and the noise level for all three systems are nearly the same. Table 12 shows the manufactured units with their performance data.

Table 12 Performance Data Micro-CHP System

Micro-CHP Technology	Model	P_{el} [kW]	P_{th} [kW]	η_{el} [%]	η_{th} [%]	η_{total} [%]	Fuel	Noise Level [dB(A)]	Dimensions [m]	Weight [kg]
Otto Engine	ecoPOWER 1.0	1	2.5	26.3	65.7	92	natural gas	46	1.132/1.18/0.32	100
Stirling Engine	DACHS	1	6.1	13	79	92	natural gas	45	1.9/0.86/1.34	-
Solid oxide fuel cell	BlueGen	2	1	60	25	85	natural gas	45	1.1/0.6/0.66	195

Economic Data

Besides performance data, economic analysis is another key factor for the decision to adopt CHP systems. The costs of implementing a Micro-CHP system include the capital cost of equipment, installation, maintenance and fuel cost. The capital cost of Micro-CHP systems arises between \$20,000 for the reciprocating engines and \$30,600 for the fuel cell. For those investments, the U.S. government gives a Business Energy Investment Tax Credit (ITC) for CHP systems. Credits of 10% for the combustion engines and 30% for fuel cells are available [42]. The incentives for fuel cells are limited to a maximum of \$1,500 per 0.5 kW. If biomass were used as a fuel source even further incentives would be possible. Since, for this case study the influence of biomass is not considered, therefore those incentives cannot be applied. Furthermore, natural gas and electricity prices are a significant factor for CHP application. In the USA the prices for natural gas and electricity are relatively low. The employed rate structure is taken from the following references: [17],[18],[44]. All calculations are performed with a fixed rate structure, special demand rates, or day and night rates are not considered. But, the revenues for sold excess electricity are taken into account. For Atlanta the rate for sold electricity is even higher, than the purchased electricity. From an economic perspective it would make sense to sell all generated electricity and purchase the demand. Because the acquisition of CHP systems is an investment which is usually not paid for in cash, an interest rate of 3.656% is considered for the dynamic payback calculation. The interest rate is defined by Treasury Direct [38]. All detailed economic data are illustrated in Table 13 and Table 14.

Table 13 Economic Data of Micro-CHP Units in Atlanta

Variante		Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Micro-CHP	[$]	19222	20214	30627.5
Peak Boiler	[$]	3444	3444	3444
purchased electricity	[$/kWh]	0.0619	0.0619	0.0619
sold electricity	[$/kWh]	0.077	0.077	0.077
Interest	[%]	0.03656	0.03656	0.03656
Incentives	[$]	1922	2021.4	6000
Sum of Investments	[$]	20744	21637	28072
Maintanance CHP	[$/kWh]	0.05	0.05	0.07
Maintanance Boiler	[$/kWh]	0.03	0.03	0.03
Fuel Cost	[$/kWh]	0.023	0.023	0.023

Table 14 Economic Data of Micro-CHP Units in Chicago

Variante		Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Micro-CHP	[$]	19222	20214	30627.5
Peak Boiler	[$]	3444	3444	3444
purchased electricity	[$/kWh]	0.152	0.152	0.152
sold electricity	[$/kWh]	0.152	0.152	0.152
Interest	[%]	0.03656	0.03656	0.03656
Incentives	[$]	1922.2	2021.4	6000
Sum of Investments	[$]	20744	21637	28072
Maintanance CHP	[$/kWh]	0.05	0.05	0.07
Maintanance Boiler	[$/kWh]	0.03	0.03	0.03
Fuel Cost	[$/kWh]	0.029	0.029	0.029

Results

This chapter shows the simulation results of the different Micro-CHP systems operating in the described homes. The focus is on performance, emission and economic results. The simulation is based on a heat oriented calculation only.

Performance

Simulations are done with each engine for each city. In Table 15 and

Table 16 the performance results are presented. With the 1 m^3 thermal storage tank the produced heat of the Micro-CHP systems equals the full heat demand of the building in most cases. With heat oriented operation the heat output of the different Micro-CHP systems is similar to the demand (only depending on the city). The electricity output varies as a byproduct. The monthly heat and electricity output is shown in Figure 35 to Figure 40 in Appendix E.

Table 15 Performance Results for Micro-CHP Systems in Atlanta

Variante		Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Heat Demand	[MWh/a]	4.7	4.7	4.7
Heat Generation CHP	[MWh/a]	4.68	4.68	4.67
Power Generation CHP	[MWh/a]	1.87	0.77	9.35
Thermal Storage Tank	[m^3]	1	1	1
Percentage Covered by CHP	[%]	100	100	100
Capacity of thermal storage	kWh	23.26	23.26	23.26
CHP Operation mode		heating controlled	heating controlled	heating controlled
CHP Efficiency (based on heating value)	[%]	83%	83%	76.7%
Average full load hours	[h/a]	1873	767	4674
Operating hours	[h/a]	2974	1374	6405

Table 16 Performance Results for Micro-CHP Systems in Chicago

Variante		Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Heat Demand	[MWh/a]	7.5	7.5	7.5
Heat Generation CHP	[MWh/a]	7.53	7.55	6.25
Power Generation CHP	[MWh/a]	3.01	1.24	12.5
Thermal Storage Tank	[m^3]	1	1	1
Percentage Covered by CHP	[%]	100	100	83
Capacity of thermal storage	kWh	23.26	23.26	23.26
CHP Efficiency (based on heating value)	[%]	83%	83%	76.7%
Average full load hours	[h/a]	3012	1238	6249
Operating hours	[h/a]	4079	2001	7319

The result for the overall efficiency needs to be explained. Looking at Table 15 and Table 16 could lead to the conclusion that the reciprocating engines operate more efficiently. Their outcome of the total efficiency for the different cases is 83% for the internal combustion and the Stirling engine in both cities. The fuel cell has a lower efficiency performance of 77%. These efficiencies are a result of the power and heat production divided by the fuel input, and are depending on the operation and the design efficiency of the systems. The design efficiency of the fuel cell is 85%, and of the reciprocating 92%, as described in Table 12. Besides the overall efficiency, when comparing these three engines, the fuel cell achieves the best results, followed by the Otto engine, then the Stirling engine. This is due to the following reasons:

First, the fuel cell displays best the given annual heat demand. Figure 22 to Figure 27 presents the annual duration curves for each simulation. The blue curves describe the heat demands whereas the red curves describe the heat output of the Micro-CHP unit. When the red curve is above the blue one, excess heat is generated, which gets stored in the thermal storage tank. The stored heat is then used in times where the red curve is below the blue one, which means the CHP system is not operating, or cannot produce enough heat. As described in the

Section “supply concepts“, the design parameters of the chosen CHP systems are on the minimum edge of what is available on the market. Thus, the maximum heat output is often higher than the recommended 30% of the maximum. The fuel cell, however, follows this criterion and thus follows the demand very well. Hence, only a little excess heat is produced which needs to be stored in the thermal storage tank. The overproduction of excess heat is greatest with the Stirling engine. As is seen in Figure 24 and Figure 25, the thermal output is higher than the highest demand of the building. Thus, the system only operates 1,374 hours per year in Atlanta and 2,001 hours per year in Chicago. Recommended hours for sufficient operation are around 6,000 hours per year. The same is true for the Otto engine which also does not meet this requirement. With 2,974 hours per year in Atlanta and 4,079 hours per year in Chicago the values are better, but not satisfying. The question arises if the thermal storage tank can hold the generated excess heat until it is really needed. Unfortunately, this aspect could not be analyzed with the BHKW Plan program, because the function is not available. The fuel cell, however, covers a percentage between 20% and 30% of the maximum demand, as recommended, and it is able to operate for a long time on maximum load (about 10 months), thus resulting at maximum efficiency.

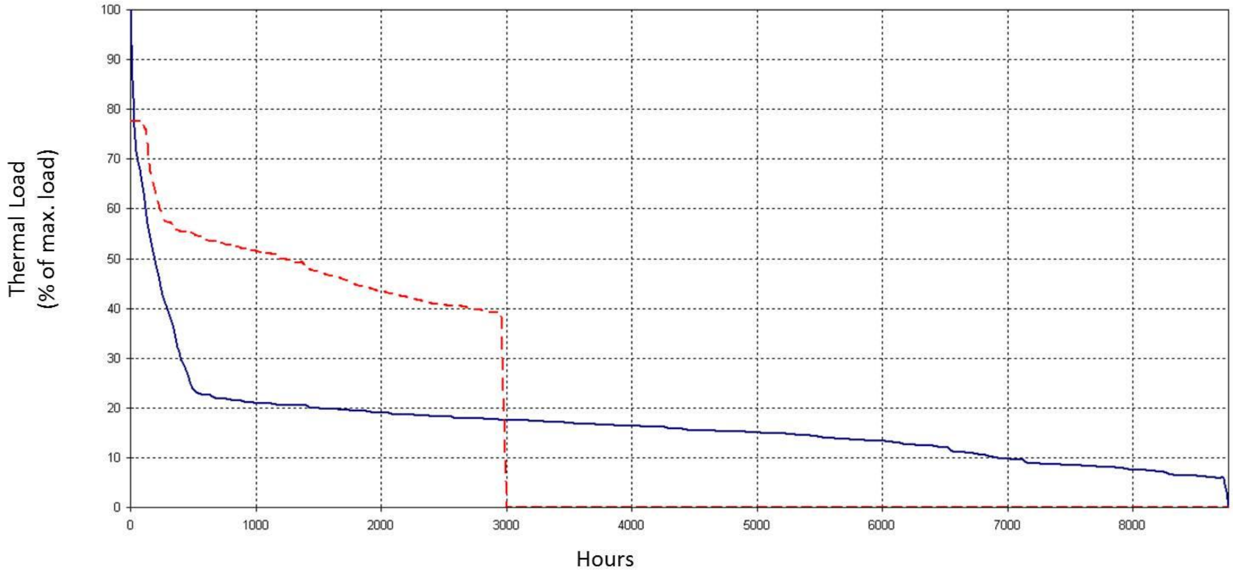


Figure 22 Annual Heat Load Duration Curve: Atlanta - Otto Engine

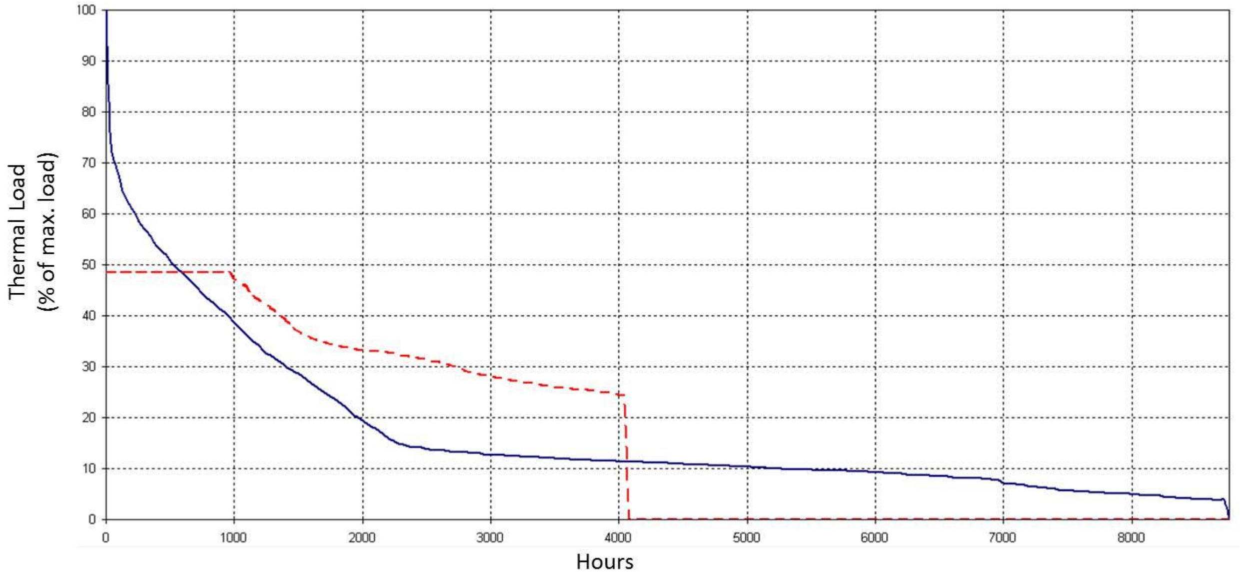


Figure 23 Annual Heat Load Duration Curve: Chicago - Otto Engine

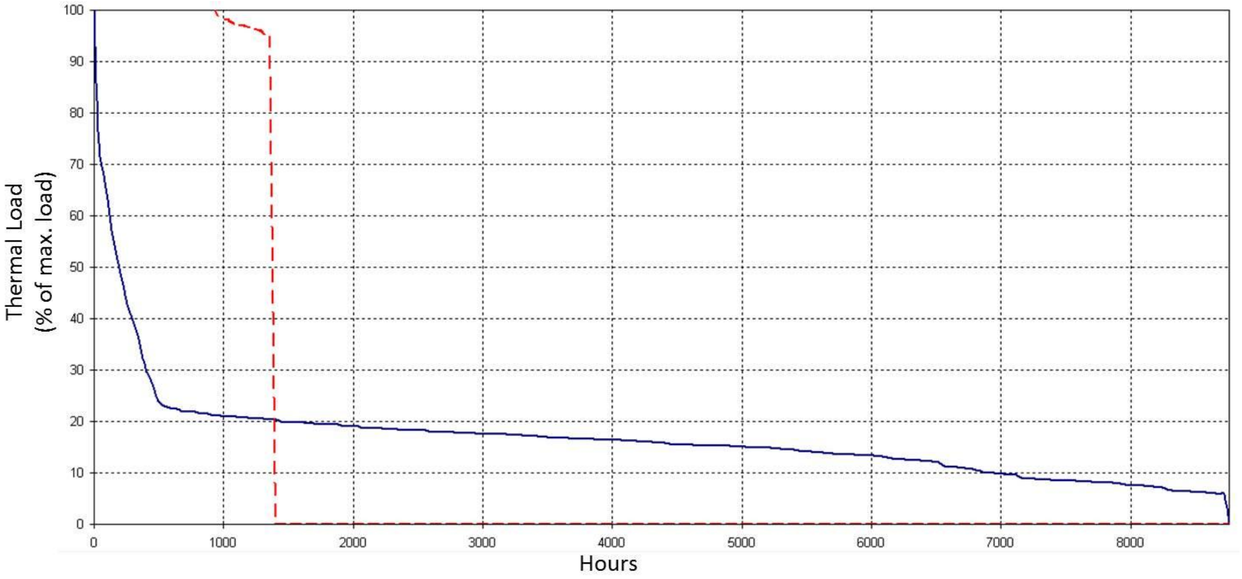


Figure 24 Annual Heat Load Duration curve: Atlanta – Stirling Engine

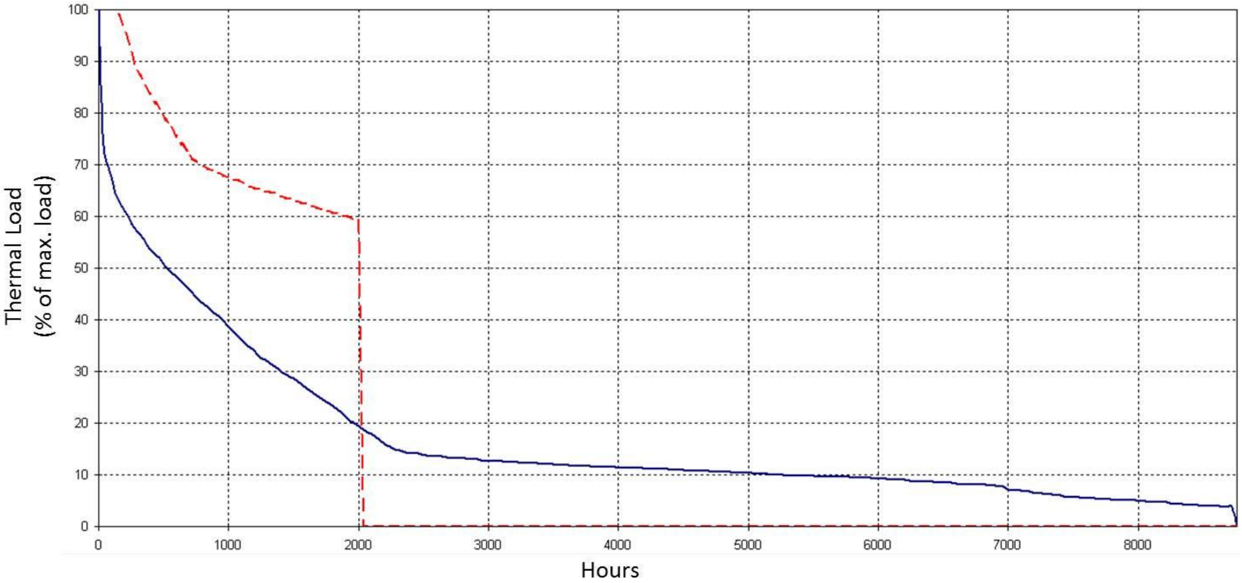


Figure 25 Annual Heat Load Duration Curve: Chicago – Stirling Engine

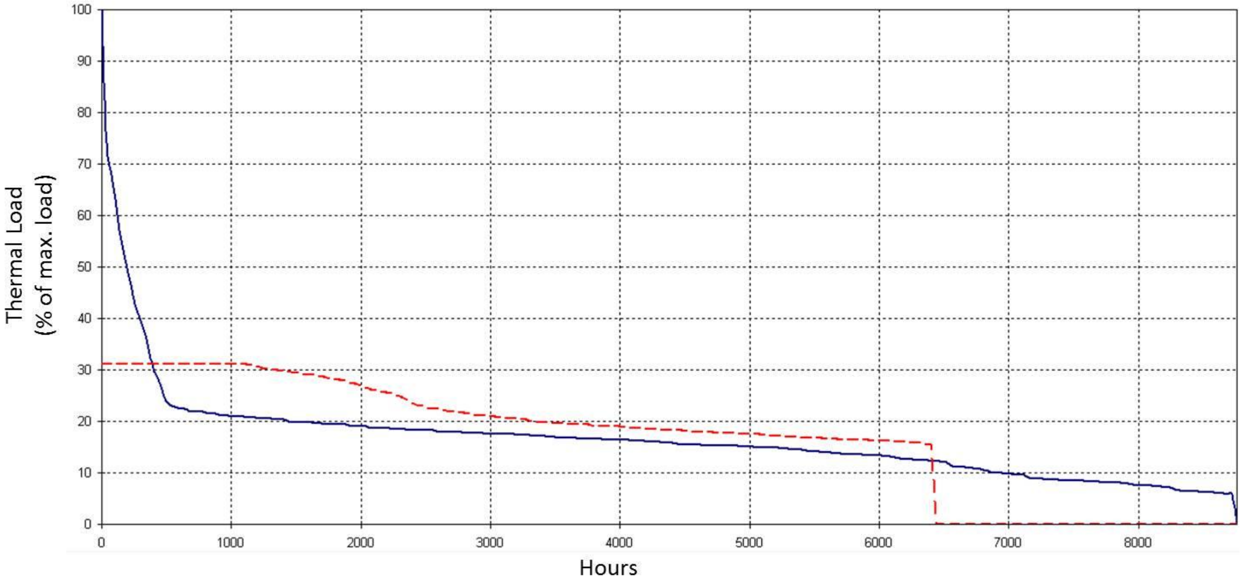


Figure 26 Annual Heat Load Duration Curve: Atlanta – Fuel Cell

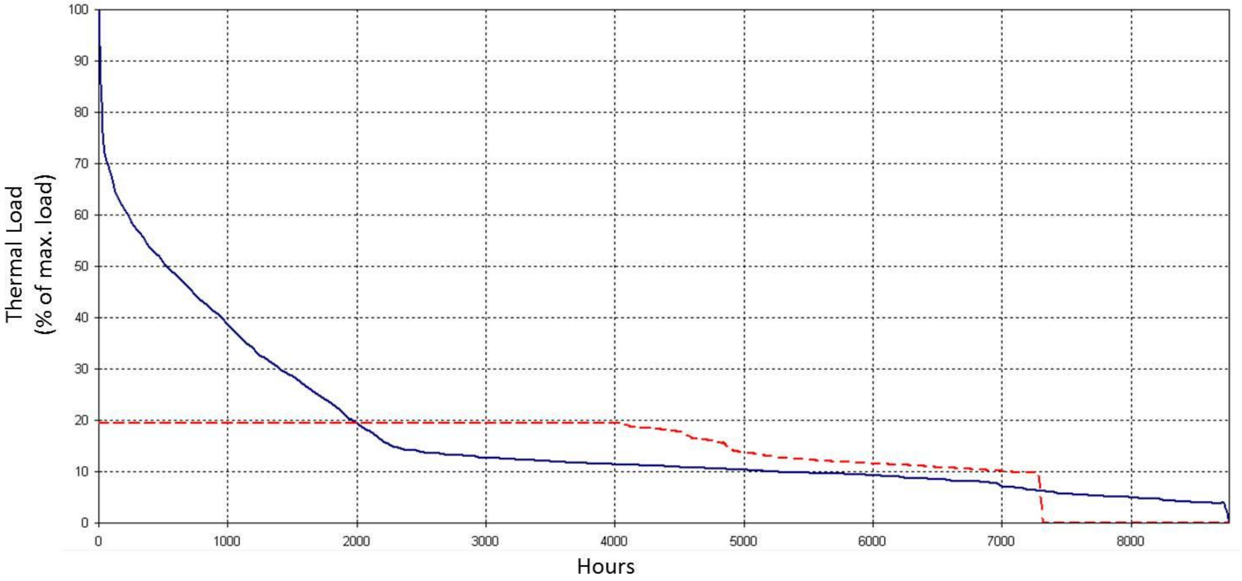


Figure 27 Annual Heat Load Duration Curve: Chicago - Fuel Cell

The next point is the performance comparison between CHP and separate heat and power generation. The performance ranking of the different Micro-CHP systems is the same as mentioned above: Fuel Cell, Otto engine, Stirling engine. The separate heat and power calculations are based on boiler and power plant performance data. For the heat generation by the boiler, the annual heat demand is considered. Atlanta’s demand is 4.7 MWh/a which results in a gas consumption of 5.7 MWh/a. The annual efficiency is 81.9%, which determines how much energy is actually used over the course of the year. The boiler efficiency of 86.7% in Chicago is slightly higher, caused by the longer and higher heat demand. The annual gas consumption is 8.7 MWh/a, as shown in Table 17.

Table 17 Performance Results Separate Heat and Power Production

Variante		Atlanta	Chicago
Heat production furnance/ boiler	[MWh/a]	4.7	7.5
Gas consumption	[MWh/a]	5.7	8.7
Annual efficiency	[%]	81.9	86.7

To calculate the fuel savings of the electricity production, the amount of electricity generated by the CHP systems is considered as a baseline. However, one must take into account the power plant efficiency and the transmission losses, and the difference is the amount of electricity needed from the power plant. Because the Stirling engine produces the least amount of electricity, compared to the other two technologies, it also obtains the least amount of fuel savings. With a higher fuel saving, the higher rate of emission savings can also be established. Detailed values are shown in

Table 18 and Table 19. The calculation of the resulting emission data based on the electricity demand is shown in the next chapter.

Table 18 Performance Results Electricity Production Power Plant – Atlanta

Variante		Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Power generated by CHP	[MWh/a]	1.9	0.8	9.3
Fuel consumption for electricity	[MWh/a]	5.2	2.1	25.8
CO_2 Emission	[t]	4.6	1.9	23

Table 19 Performance Results Electricity Production Power Plant – Chicago

Variante		Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Power generated by CHP	[MWh/a]	3	1.2	12.5
Fuel consumption for electricity	[MWh/a]	8.3	3.4	34.5
CO_2 Emission	[t]	7.4	3	30.8

Figure 28 shows the calculated fuel reduction for heat and electricity generation. The internal combustion engine achieves 3.8 to 5.5 MWh/a, the Stirling engine 1.9 to 2.5 MWh/a, and the fuel cell 15 to 19.1 MWh/a. Once more, the fuel cell significantly sets itself apart from the other two technologies. Detailed calculation tables can be found in Appendix F, Table 33 and Table 34.

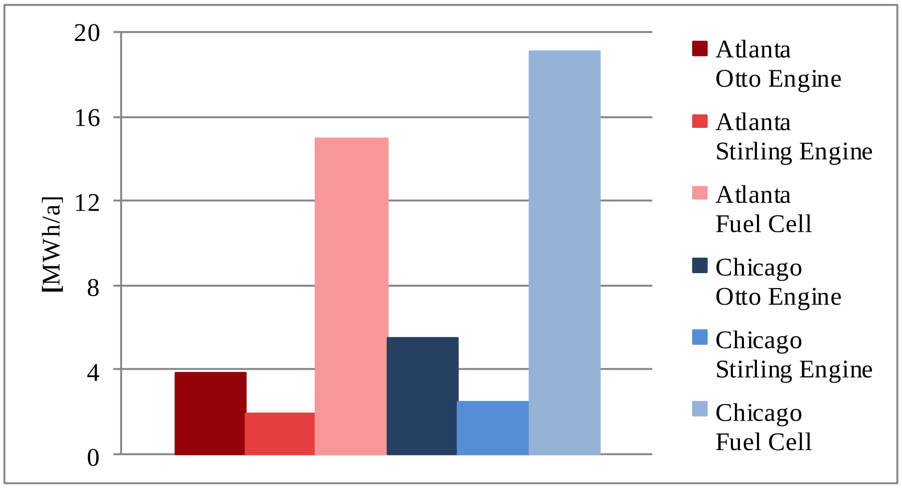


Figure 28 Fuel Savings Separate compared with Combined Heat and Power Generation

Emission

The fuel savings directly lead to the next criterion: the emission results. In a century where global warming is a genuine problem, the emission evaluation is of high importance. The emission values are a combination of the reduced fuel consumption, and the fuel combustion process. Power generation in fuel cells is not produced by combustion, but through a chemical reaction. However, the pre and post process of hydrogen generation does create emissions. The emission values for fuel cells are significantly lower than emissions from the common combustion process, as described in the chapter “Fuel Cells.”

The most important and well known measure is the carbon dioxide (CO_2) discharge. In Figure 29, the CO_2 reduction of each case is illustrated. Here, the combination of fuel consumption and the fuel combustion process is considered. Calculations are based on the fuel for the heat demand for Micro-CHP system and boiler, as well as for the power plant based on the amount of electricity produced by the CHP system, as described in the previous chapter. It can be seen that the Stirling engine shows the lowest reduction with 58% and 60%, the internal combustion engine is placed in the middle with 75%, and the fuel cell eliminates with 99% of all CO_2 emissions. It is surprising that the Otto engine achieves better results than the Stirling engine because the combustion process takes place outside of the prime mover. Thus, it can be better controlled and should achieve better values. However, even if the fuel cell CHP system is a clear winner, it needs be noted that with each system a CO_2 reduction over 50% is possible. This is very positive for all CHP systems.

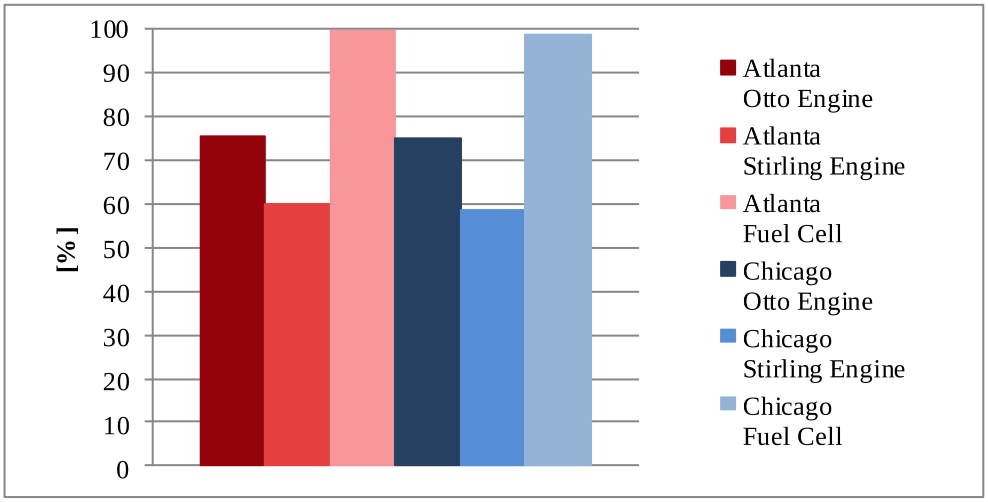


Figure 29 CO_2 Reduction for Micro-CHP Units

Besides the CO_2 values, emissions of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO_X), and dust are also calculated for each case. Methane (CH_4) and non-methane volatile organic compounds NMVOC are not calculated, because the manufacturer did not provide these data for their systems. Detailed values are given in Table 20 and

Table 21.

Table 20 Emission Results for Atlanta

Variante			Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Combined	CO_2	[t]	1.4	1.2	0.1
	CO	[kg]	1.5	0.1	0
	SO_2	[kg]	0	0	0
	NO_x	[kg]	0.7	2.3	0.1
	Dust	[kg]	0	0	0
Separate	CO_2	[t]	5.7	3	24.2
	CO	[kg]	0.3	0.3	0.3
	SO_2	[kg]	19.6	8	97.7
	NO_x	[kg]	9	4	43.2
	Dust	[kg]	0.6	0.3	3.1

Table 21 Emission Results Chicago

Variante			Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Combined	CO_2	[t]	2.3	2	0.4
	CO	[kg]	2.5	0.3	0.1
	SO_2	[kg]	0	0	0
	NO_x	[kg]	1.1	3.8	0.2
	Dust	[kg]	0	0	0
Separate	CO_2	[t]	9.2	4.8	32.5
	CO	[kg]	0.5	0.5	0.5
	SO_2	[kg]	31.5	12.9	130.6
	NO_x	[kg]	14.5	6.4	57.9
	Dust	[kg]	1	0.4	4.1

Economics

The comparison of costs and returns is necessary to determine the cost efficiency of the Micro-CHP systems. The cost of the CHP systems can be derived from the investments which are calculated with the annuity method comprising the annual capital, annual operating and annual fuel costs. The revenues generated by the electricity supply (avoided purchase of electricity) were subtracted from the calculated investment costs of the CHP. Also, the credits from the heat must be deducted to calculate the specific electricity generation costs. The cost of the separate heat and power system can be divided into the same categories as for the combined generation to determine these credits.

The calculations are based on descriptions in chapter II. The annual capital costs are based on an amortization time of ten years for the CHP systems and the boilers. Out of this, the yearly redemption rate to the bank is obtained. An interest rate of 3.656% is considered as debt interest rate, and 0.25% as credit interest rate.

Separate Heat and Power Production:

For separate heat and power generation only the acquisition cost for the boiler, as well as the fuel and electricity cost are added together. As it can be seen from Table 22, the cost for natural gas and electricity are higher in Chicago than for Atlanta. The higher amount for electricity can be ascribed to the higher rate structure in Chicago, since the Section "Energy Requirements for Residential Buildings" showed that the electricity demand for Chicago is about 4 MW less than Atlanta's. For the fuel costs, the result is a combination of higher rates, but also a longer and colder winter/ heating period.

Table 22 Economic Calculation for Separate Heat and Power Production

Variante		**Atlanta**	**Chicago**
Capital Cost	[$/a]	417.38	417.38
Operating Cost	[$/a]	141	225
Fuel Cost	[$/a]	115.75	229.60
Total Cost	[$/a]	674.13	871.98

Combined Heat and Power Production:

The calculation of the total costs for the CHP system shows that the lowest costs are with the Otto engine, followed by the Stirling engine, and the highest costs have the Fuel Cell CHP. The main factor for this ranking is the capital costs. The operating costs are the result of the maintenance cost and the electricity produced during the year. The more electricity produced, the higher the operating cost. This is contrary to the earnings because the more electricity the system produces the more revenues the operator gets. From Table 23 and Table 24, the results for the individual costs are shown. At first glance, it seems that the total costs of fuel cells are much higher than for the other two systems. This increase is due to the high investment costs of fuel cells and the thermal output being smaller than the electrical output (which means that the system has to operate longer). However, the Chicago option with fuel cell option is the only one where operational plus fuel costs are smaller than the earnings. Hence, it is the only combination for which the capital expenditures can be compensated for by the earnings.

Table 23 Economic Results Atlanta

Variante		Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Capital Cost	[$/a]	2,096.54	2,204.74	2,984.60
Operating Cost	[$/a]	93.50	38.50	654.50
Fuel Cost	[$/a]	182.69	152.01	423.17
Earnings	[$/a]	143.77	59.20	718.83
Total Cost	[$/a]	2,228.97	2,336.06	3,343.44

Table 24 Economic Results Chicago

Variante		Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Capital Cost	[$/a]	2,096.54	2,204.74	2,984.60
Operating Cost	[$/a]	150.50	62.00	875.00
Fuel Cost	[$/a]	365.42	304.75	703.46
Earnings	[$/a]	457.52	188.48	1,900.00
Total Cost	[$/a]	2,154.94	2,383.01	2,663.06

In order to satisfy the additional investment for a CHP system compared to a regular boiler, the breakeven point for the return of investment needs to be calculated. Since the capital expenditures for the CHP systems are much higher than for the boilers, it is obvious that the CHP system will have a higher total costs in the first 10 years where the loan is being paid back. The question is: How much can the earnings compensate this difference and how is the relationship after the ten years? For the comparison, the cost difference between the CHP and boiler is treated as avoided cost. It needs to be noted that with avoided cost the amount of money you save by not buying the CHP system is described. Figure 30 presents the avoided costs of each version. Looking at those graphs, it is clear that none of those combinations break even. Thus, all units have their payback outside of their lifetimes. And even worse: for the building in Atlanta operating with the fuel cell CHP system, the sum of operating and fuel cost is still higher than the returns from the electricity production even after the acquisition time, shown by the still rising columns for the savings. There, a recovery of the acquisition cost can never be achieved. Appendix G shows the relationships between the costs for a CHP and costs for a boiler for each individual version. It turned out that currently Micro-CHP is not feasible for any of the CHP technologies at these locations.

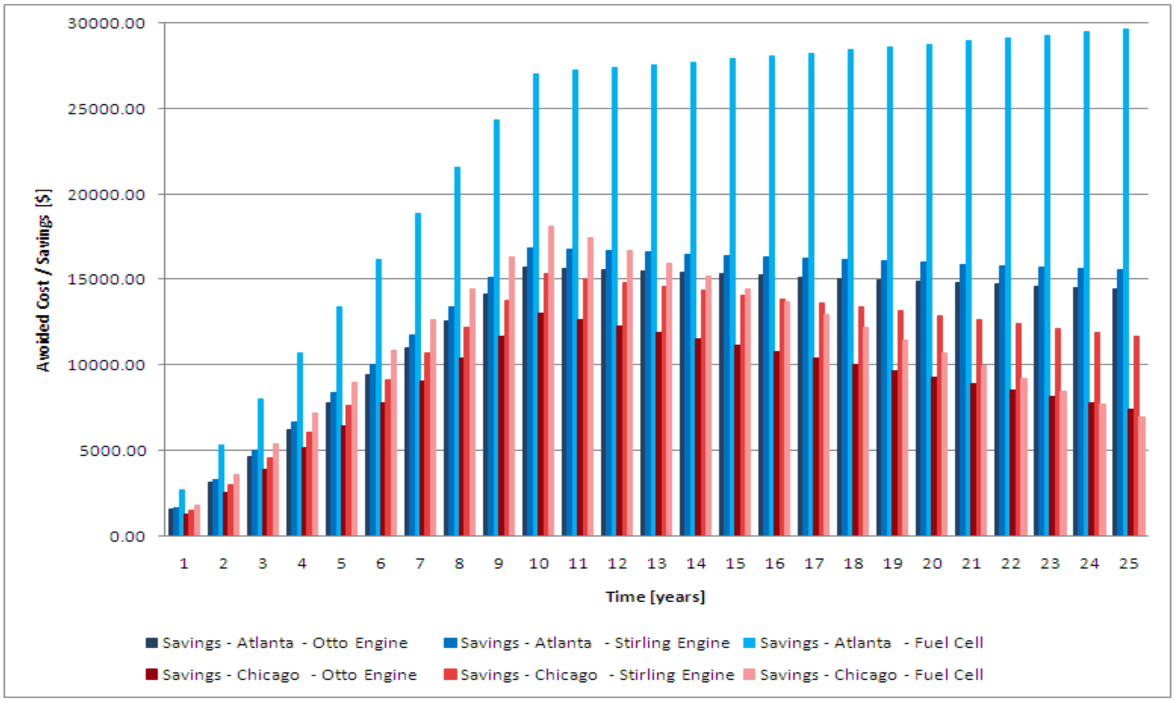


Figure 30 Avoided Cost if no CHP is acquired

Now, the question arises as to what has to happen for the use of Micro-CHP to become reasonable. Three different factors are influencing the outcome: first, the heat demand of the buildings, second the investment cost for CHP, and third the cost for energy. The heat demand is dependent on the location, which is assumed to be fixed. The cases for change in investment cost and energy costs were calculated with the goal to get a return of the additional investment before the lifetime of the equipment ends. With a lifetime of 15 years, the investigation of the acquisition cost shows that for Atlanta a cost reduction of minimum 71% would be necessary. The exception is the fuel cell CHP system, because the operation and fuel cost are always higher compared to a boiler. Better results can be achieved in Chicago, the Otto engine achieves 52% reduction, and the Stirling engine 62%. The best situation seems to be the fuel cell with 38% reduction, even while the acquisition costs are the highest. Due to the higher investment and higher returns from the power generation, the financial situation is better.

Table 25 Percentage Reduction of Investment Cost

		Otto Engine	Stirlilng Engine	Fuel Cell
Atlanta	[%]	71%	73%	-
Chicago	[%]	52%	62%	38%

Similar conclusions can be drawn by investigating the increase in energy cost. The percentage of energy cost increase, which would be necessary to establish a return after 15 years of operation, was calculated. As shown in Table 26, the increase would amount to several hundred percent, which is unreasonable. Again, the only good system is the fuel cell operating in a Chicago building. With a 66% increase of energy cost the CHP system would be paid off after 15 years.

Table 26 Percentage of Energy Cost Increase

		Otto Engine	Stirlilng Engine	Fuel Cell
Atlanta	[%]	1304%	4680%	443%
Chicago	[%]	227%	814%	66%

Figure 31 graphically shows the trend for the different CHP systems including the rise of energy cost shown in Table 26. After 10 years the high acquisition costs are paid back and through the income the ROI is reached after 15 years.

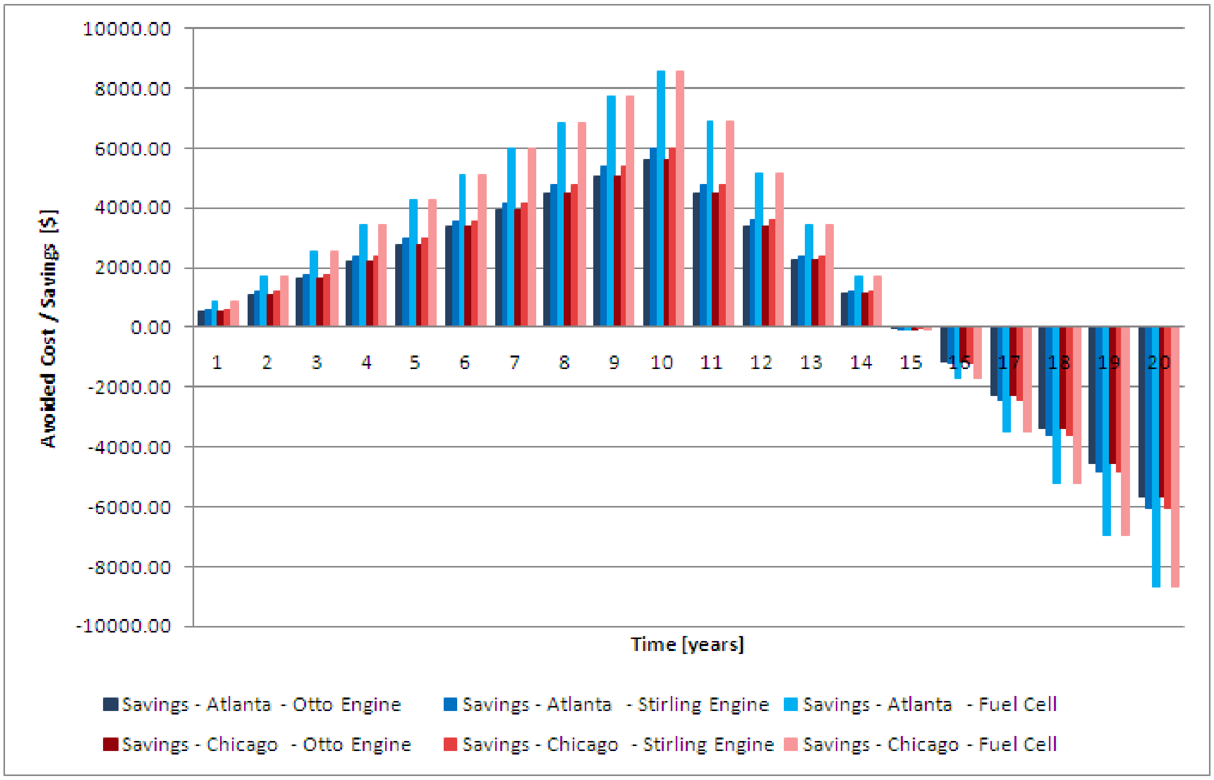


Figure 31 Savings if no CHP acquired and Return of Invest within 15 Years

CHAPTER VI

TECHNIQUES TO IMPROVE ECONOMIC BENEFITS

CHP displays an important role in the Smart Grid application. The term Smart Grid encompasses communication network, control of power generators, storage, electrical consumer, and main power equipment for power transmission and distribution networks of electricity supply, from major power plants all the way to residential homes. Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies. In its application micro-CHP helps to balance supply and demand, operating as a source of electricity that can be dispatched remotely and modulated to meet the needs of the network and the consumer. The output of micro-CHP units can be aggregated and used as a source of electricity output to supplement shortfalls in demand from centralized generation.

Micro-CHP coupled with heat storage can play several “smart” roles on the new grid. In times of rapidly falling electrical output from renewables it can start to supply the local electricity network and using heat storage temporarily store the heat to supply later. This also keeps the electricity supply local hence minimizing grid losses. In times of falling demand CHP can switch off supplying heat from storage. This functionality can be controlled by suitable balancing and demand response markets signaling the appropriate action. Such deployment maximizes the value of the appliance for both end-user and distribution utility.

There is also the opportunity that “smart” operation of micro-CHP can enable load-shifting for end users, by decoupling end-user peak demand from traditional peaks in network demand, which are also associated with the operation of high cost peak generation. This load-shifting from peak periods has numerous benefits.

- Demand and supply are better balanced
- Wholesale price volatility is reduced, leading to customer price benefits
- Distribution losses from central plant are avoided through local production and use
- Reserve generating capacity is available to the utility network operator to meet its obligations to respond to frequency variations and maintain network integrity

Micro-CHP is a flexible and controllable player in the new smart grid low carbon electricity market offering services to the grid and the opportunity to bring a whole new group of citizens into a new relationship with the energy market.

CHAPTER VII

DISCUSSIONS AND CONCLUSIONS

This thesis shows the various aspects in the field of Combined Heat and Power. First, the term of the CHP was defined and the various technologies classified. This was followed by a detailed consideration of the stage of development. CHP is a well proven technology, recognized worldwide as a cleaner alternative to traditional centralized power generation. The highest level of development and the highest penetration have been achieved by CHP systems with combustion engines. However, there are already alternative and innovative systems like Stirling CHP, micro turbines, and CHP systems with process steam operations ready for commercialization. The work includes further manufacturers directories for the various technologies. Attention should be paid to the different investment costs and the sometimes very different (electrical) efficiencies of each technology. This requires a detailed examination of the usage, to determine which system best fits the given requirements. Besides all the advantages for CHP some barriers remain, but the U.S. government is working on reducing, or maybe eliminating those barriers.

In the second part of this thesis, a case study is analyzed for residential application. The technical, environmental and economical feasibility of using Micro-CHP systems in the north and south of the USA were investigated. The following conclusions can be deduced: Looking from the perspective of performance and emissions, the CHP system based on the fuel cell achieved the best results. The reason for this is the lower heat-to-power ratio of the system. The thermal output best fits to the heat demand of the buildings. Thus, fuel cell systems can be operated better in the optimum efficiency range compared to the combustion engines. This also decreases the fuel consumption of the system. The fuel cell system uses between 15% and 19% less fuel compared to a separate heat and power system, while the reduction for the combustion engines is significantly less and lies between 2% and 5.5%. The fuel reduction as well as the way power is generated leads to the very high emission reductions for the fuel cell. Prevention of over 90% of the CO_2 emissions is possible. But also for the combustion engines, a significant drop can be achieved (60% for Stirling and 75% for Otto engine). Fuel cell operation may result in zero emissions with a hydrogen production using electrolysis. With these results a major reduction in greenhouse gases can be achieved. This makes the emission factor of the highest benefit for combined heat and power generation. However, hydrogen generation by electrolysis is more cost intensive.

From an economic point of view, Micro-CHP for residential buildings in the U.S. is currently not attractive. The annual savings turned out to be too low to return the investment cost in a reasonable time. The operation in Atlanta with the fuel cell CHP system shows even higher operation costs than for the boiler. Several reasons can be deduced: First, the heat demand is not high enough for systems available on the market, reducing the efficiency. Also the acquisition costs are too high and electricity cost too low. Further, federal or state incentives could help to reduce the investment cost. However, the analysis of a decrease in investment cost and an increase in energy cost showed that too high price changes would be necessary which cannot be expected in future. The only viable combination is the fuel cell application in Chicago, for future use, which confirms that Micro-CHP is of more value for cold climates. It therefore can be concluded that currently there is no economic potential of CHP in the U.S. However, the effects of global warming, and the environmental benefits of CHP should be considered. With possibly higher incentives, Micro-CHP systems could become more attractive for home owners and thus more competitive to conventional heating systems.

Based on these findings further studies can be recommended based on bigger CHP systems, e.g. for light commercial buildings, hospitals, or residential communities which have a higher advantage of using the heat energy. The systems could better match the demand and would operate more continuously and thus more efficiently. Also promising would also be applications where a tri-generation with absorption chillers would be possible. This further application could help increase efficiency and reduce cost. Determining the appropriate sizing on a regional basis with various climates would provide valuable information for the feasibility. Another promising investigation would be the implementation of other renewable energy sources, such as solar systems or different bio fuels. Solar systems could have a positive effect on adjusting the power and heat production based on a sustainable energy source. The usage of bio fuels can bring various environmental benefits. The economic solution could be very uncertain, since bio fuels are in general more expensive than natural gas, however, special incentives could be applied.

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APPENDIX A

MARKET SURVEY – MANUFACTURER LISTS

Steam Turbine

Table 27 Technical Data for Steam Turbine Manufactures

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
Adoratec GmbH Breite Seite 1 74889 Sinsheim Germany +49 (0) 431/5708924 http://www.adoratec.com/	300 625 1000	1350 2665 4270				Biomass
Pratt & Whitney 400 Main Street East Hartford, CT 06108 United States +1 860-565-4321 http://www.pw.utc.com/	968	4081	18.8			Wood biomass: sawdust, wood chips, bark, treated wood Other biomass: dried sewage sludge, straw, green cuttings, rice husks, etc. Waste material
Steam Systems Pty Ltd Campbellfield, Victoria 03 9357 1030 Australia www.steamsystems.com.au/	140 1050	1100 7000				Wood Chips/Sawdust

Gas Turbine

Table 28 Technical Data for Gas Turbine Manufacturers

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
2G - CENERGY Power Systems Technologies Inc. 151 College Drive - 15 Orange Park, FL 32065 USA +1 904 579 3217 http://www.2g-cenergy.com/	100-1060 100-1060		36-39 35-41	47-53 48-54	86-90 88-89	biogas natural gas
CAPSTONE TURBINE CORPORATION 21211 Nordhoff Street Chatsworth, CA 91311 USA Tel: +1 818.734.5300 www.capstoneturbine.com	30-1000 29-65		26-33 25-29			natural gas landfillgas digester gas propane diesel aviation kerosene

Table 28 continued

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
Dresser-Rand CHP solutions 760 Chief Justice Cushing Hwy Cohasset, MA 02025 USA +1 781-333-0304 http://www.dresser-rand.com/	502 1296	497 5.12	42 40.3	41.5 49.1	83.5 89.5	natural gas biogas
Eliott Energy Systems Inc. 2901 S.E. Monroe Street Stuart, FL 34997 USA +1 772-219-9449	100	172			75	natural gas
GE Energy http://www.ge-energy.com/	510 MW				61-87	natural gas
Ingersoll Rand 30 New Hampshire Av. Portsmouth, NH 03801 USA +1 877-477-6937 http://www.ingersollrandproducts.com/energy/	70 -250		28-30			natural gas biogas landfil gas sewage gas
KAWASAKI Gas Turbine Europe GmbH Nehringstrasse 15 61352 Bad Homburg Germany + 49 (0) 6172-73 63-0 www.kawasaki-gasturbine.de	509 1226		17.3 22.2	57.5 55.2	74.3 77.4	natural gas
Micro Turbine Technology B.V. De Rondom 1 Eindhoven, 5612 AP Netherlands +31 88-6880000 www.mtt-eu.com	3	15				natural gas
SiemensAG Freyerslebenstr. 1 91058 Erlangen Germany +49 1805247000 http://www.energy.siemens.com/	8-520MW					natural gas biogas syngas fuel oil
Turbec S.p.A. Via Statale, 20/A 440 40 Corporeno (FE) Italy Tel: +39 0516835273 www.turbec.com	100	155	33		77	natural gas kerosene meghanol LCP

Internal Combustion Engine

Table 29 Technical Data Internal Combustion Engines

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
AISIN Seiki Co., LTD. 3-3, Aioi-cho Kariya, Aichi Japan +81 448-8525 www.aisin.com	4.6	11	25	69	85	natural gas
CENERGY 151 College Drive - 15 Orange Park, FL 32065 USA +1-904-579-3217 www.2g-cenergy.com	27-450 540-2994	97-567 667-3062	34.2-38.2 37.2-42.3	63.9-51.7 49.8-43.3	98.1-89.9 87-85.6	natural gas
green energy solutions GmbH Greifenthaler Strasse 28 35630 Ehringshausen-Katzenfurt Germany +49 6449-717403-400 www. green-energy-solution.de	5-6.5	16-Dec			90	natural gas petroleum bio gas
Honda Motor Europe GmbH Kundenzentrale Postfach 200222 63077 Offenbach Germany +49 01805 20 20 90 www.honda.de	1	2,5	26.3	65.7	92	natural gas
Kirsch GmbH Biewerer Strasse 231 54293 Trier Germany +49 651-96600 www.kirsch-homeenergy.de	8-12	2-4	25	70	95	natural gas
Kraftwerk Kraft-Waerme-Kopplung GmbH Zur Berrfedernfabrik 1 30451 Hannover +49 511-2629970 http://kwk.info/	16.5	19-35.3	31.5	69.5	101	natural gas
LichtBlick AG Zirkusweg 6 20359 Hamburg Germany +49 (0)40 - 80 80 30 31 www.lichtblick.de	19	32			90	natural gas

Table 29 continued

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
MTU onsite solution Maybackplatz 1 88040 Friedrichshafen Germany +49 7541 900						natural gas bio gas
SenerTec Carl-Zeiss-Strasse 18 97424 Schweinfurt Germany +49 (0)9721 6510	5-5.5	10.512.5	26-30	59-61	88-89	natural gas petroleum bio diesel fuel oil
Tecogen Inc. 45 First Avenue Waltham, MA 02451 USA +1 781-466-6400 http://www.tecogen.com/	60 75	135 150	26.4 27.1	67.3 64.5	93.7 91.6	natural gas
Vaillant Group 42850 Remscheid +49 (0)2191 - 18 2754 www.vaillant-group.com	1-4.7 1-4.7	2.5-13.8 2.5-13.8	26.3 26.3	65.7 65.7	92 92	natural gas

Steam Engine

The market share for steam engines in conjunction with CHP is relatively low. In the following table, producers only from Australia and Germany are presented. Unfortunately, the amount of available data is also very low.

Table 30 Technical Data for Steam Engine Manufacturers

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
lion energy GmbH & Co. KG Zur Hammerbrücke 9 59939 Olsberg Germany +49 (0)2962 88 13 39 http://www.powerblock.eu/	0.3 - 2	16.3			94	natural gas, petroleum wood chips, fuel oil

Table 30 continued

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
OTAG Vertriebs GmbH & Co.KG Zur Hammerbrücke 9 59939 Olsberg Germany +49 2962-881339 http://www.powerblock.eu/	0.2-3	16.2			98.5	natural gas, petroleum
Spilling Energie Systeme GmbH Werftstrasse 5 20457 Hamburg Germany +49/(0)40-789175-0 http://www.spilling.de/index.php	140-1050	1100-7000				natural gas
Steam Systems Pty Ltd Campbellfield, Victoria 03 9357 1030 Australia www.steamsystems.com.au/	140 1050	1100 7000				Wood Chips/Sawdust

Stirling Engine

Table 31 Technical Data Stirling Engine

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
Baxi Conventry Road Warwick, CV 34 4LL United Kingdom +44 844-871-1525 www.baxi.co.uk	1	24				natural gas petroleum
CLEANERGY AB (HQ) Theres Svenssons gata 15 417 55 Göteborg Sweden www.cleanergyindustries.com	2-9	8-25	22-24.5	65.5-68	90	biogas, landfill gas, sewer gas, natural gas
Disenco Energy plc Sheffield Business Park Sheffield, South Yorkshire United Kingdom +44 (0)114 261 5180	3	16	16	84	90	natural gas

Table 31 continued

Manufacturer	**P_{el} [kW]**	**P_{th} [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
KWB Industriestraße 235 8321 St. Margarethen/Raab Austria +43 3115-61160 www.kwb.at	8 - 30 20 - 50	8.4 - 31.4 21,4 - 55.4			95 90	wood pellet wood logs
Microgen Energy Limited Minerva Business Park Lynch Wood, Peterborough UK +44 1733-361002 www.microgen.com	1.1	15-36	30	60	90	natural gas
Senertec Carl-Zeiß-Straße 18 97424 Schweinfurt +49 9721-6510 http://www.senertec.de/en/	1-5.5	6.1-14.8	13-27	75-76	89-92	natural gas propane
Stirling Biopower Inc. 275 Metty Drive Ann Arbor, Michigan 48103 USA www.stirlingbiopower.com	2-9.5 38-43	8-26 105-122	22-24 27-28	70-72 48-52	86-92 75-80	biogas, natural gas, petroleum
SUNMACHINE GmbH Daimlerstraße 21 87437 Kempten Germany +49 831-5407777 www.sunmachine.com	1.5 - 3	4.5 - 10	20 - 25	65-70	90	wood pellets
Viessmann GmbH & Co KG Viessmannstraße 1 35108 Allendorf +49 6452-700 www.viessmann.de	1	3.6-26	15		90	natural gas
Whisper Tech Ltd Wellington, 6143 New Zealand +64 3363 9293 www.whispergen.com	0,4 – 1,2	4,9 – 8	12	78	> 90	natural gas

Fuel Cell

Table 32 Technical Data for Fuel Cell

Manufacturer	**Technology**	**P_{el} [kW]**	**$P_{th\ (250°F)}$ [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
Baxi Innotech Ausschläger Elbdeich 127 20539 Hamburg Germany +49 40-236676-00 www.baxi-innotech.de	PEM	1	1.8	32	59	97	
Bloom Energy 1299 Orleans Drive Sunnyvale, California 94089 USA +1 408-543-1500 http://www.bloomenergy.com/	SOFC	105 210		50 50			natural gas
CSIRO 170 Browns Road Noble Park, Victoria, 3174 Australia +61 39554-2300 http://www.csiro.au/	SOFC	2	1	60	25	85	natural gas
Ceramic Fuel Cells Ltd. Unit 8, Candy Park, Hardknott Road Bromborough,Wirral CH62 3QB, United Kingdom +44 (0)151-334-8880 http://www.bluegen.info/	SOFC	0-2000	300-1000	60	25	85	natural gas
Clear Edge Power 7175 NW Evergreen Parkway Hillsboro, OR 97124 USA +1 877-257-3343 http://www.clearedgepower.com/	SOFC	5	5.8			90	natural gas
FuelCell Energy 3 Great Pasture Road Danbury, CT 06813 USA +1 203-825-6000 www.fuelcellenergy.com		300 1400	140668 649415				natural gas
HEXIS AG Zum Park 5 Postfach 3068 8404 Winterthur Switzerland +41 52-262-6311 www.hexis.com	SOFC	1	2	30	66	95	natural gas bio methane

Table 32 continued

Manufacturer	**Technology**	**P_{el} [kW]**	**$P_{th\ (250°F)}$ [kW]**	**η_{el} [%]**	**η_{th} [%]**	**η_{total} [%]**	**Fuel**
Mitsubishi http://www.mhi.co.jp/en/	SOFC					55 65	coal natural gas
UTC Power 195 Governor's Hwy South Windsor, CT 06074 USA http://www.utcpower.com/	SOFC	400	280	42	48	90	natural gas
Vaillant Group 42850 Remscheid +49 (0)2191 - 18 2754 www.vaillant-group.com	SOFC	2	1	30-34	50-51	80-85	natural gas

APPENDIX B

BUILDING DIMENSIONS

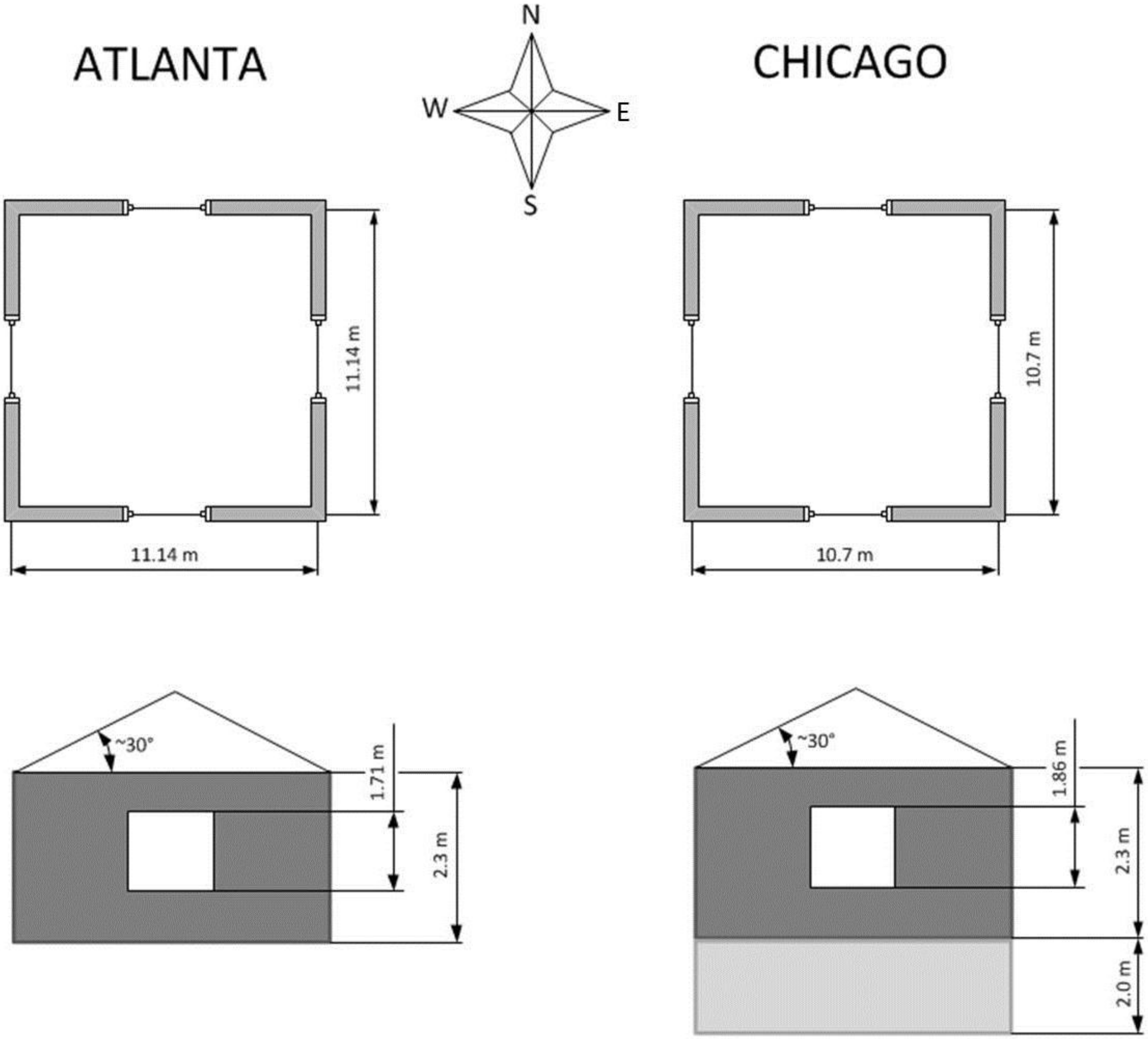

Figure 32 Building Dimensions [16]

APPENDIX C

BUILDING LOAD SIMULATION WITH TRNSYS

TRNSYS is a transient simulation program developed at the University of Wisconsin-Madison in 1975. The program package includes calculations for the thermal performance of a building including active and passive components for the power supply (e.g. boilers, heat distribution system, collector systems) and the evaluation of the occurring time-dependent energy flows. TRNSYS was originally developed for the detailed analysis of buildings designed with active solar technology. Today, passive solar components as well as conventional heating and cooling equipment models are available. The advantage of TRNSYS is its flexibility and the ability to simulate a system in great detail. TRNSYS is based on a modular structure. It contains a large number of standard components; these so called types can be tied together as required to simulate the real system. The open structure of the program allows the user to incorporate material-created types and to modify existing standard components. Each type describes a particular system component, while the actual performance of the components is simulated with mathematical algorithms. TRNSYS uses different solution algorithms to solve the equations arising from the individual components and their logical connections in the entire system. The simulated time step size and accuracy is selectable by the user. In principle, all input and output variables of each component are displayed. The output values can also be integrated over defined time intervals (days, months, years).

In this case study TRNSYS is used to develop the heating and cooling loads of the building. Figure 33 illustrates the structural configuration of the building model. The design is the same for both locations, only the parameters are different. All parameters are included as described in the Section “Building Loads”.

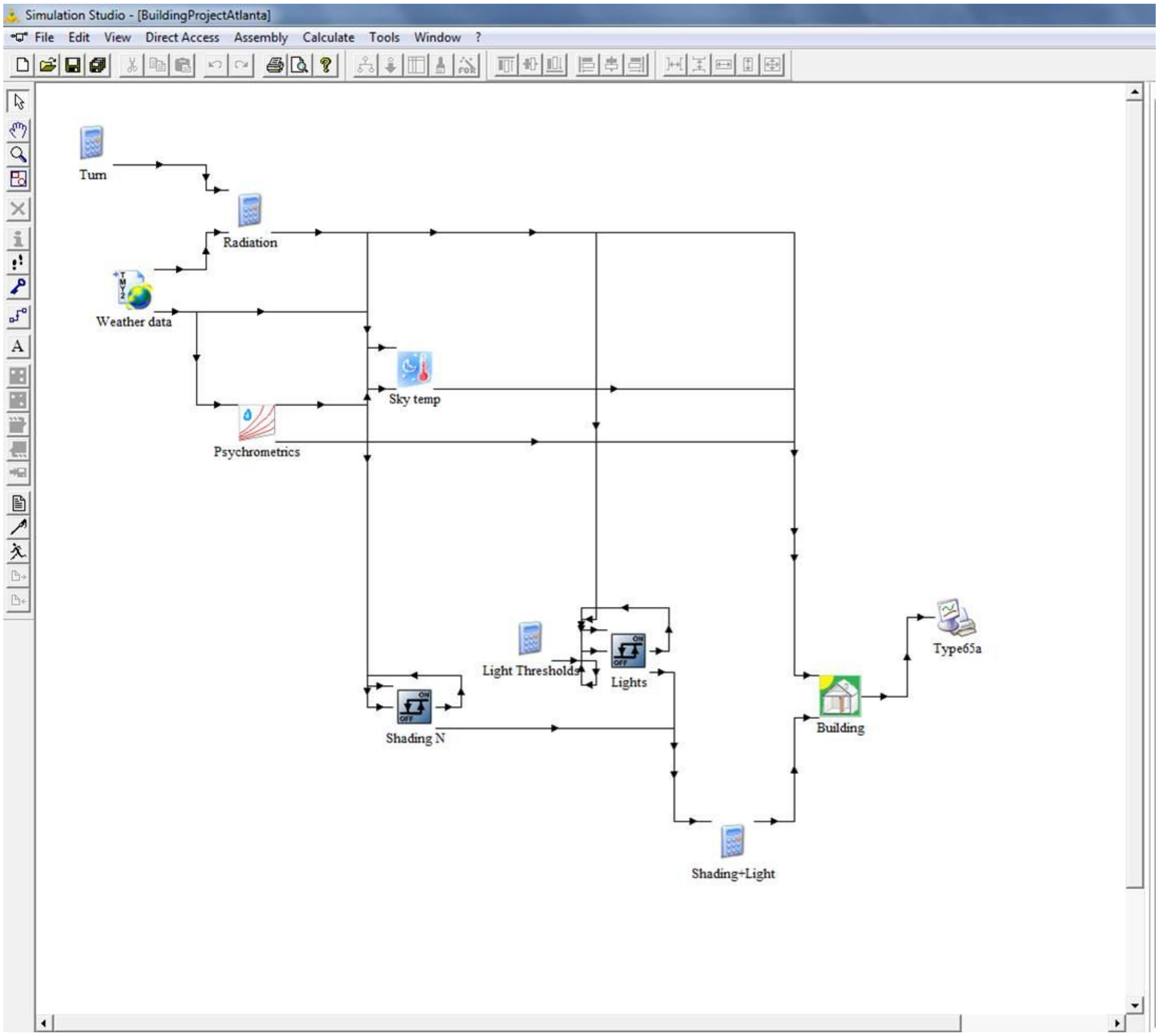

Figure 33 TRNSYS Model for Heating and Cooling Load Simulation

APPENDIX D

BHKW PLAN SOFTWARE

BHKW-Plan is software for the design of CHP plants. It is based on the research project "Economic and usable potential of combined heat and power in Baden-Württemberg" initiated by the Department of Commerce and was developed by the Center for Solar Energy and Hydrogen Research Baden-Wuerttemberg, Germany, and the Institute of Technical Thermodynamics at the German Research Institute of Aeronautics and Astronautics, supported by the Ministry of Economic Affairs Baden-Wuerttemberg, Germany. Since 2003 the program was developed and marketed by the company "Steinborn Innovative Building-Energy Supply".

BHKW-Plan is an Excel interface based program. The basic components are the heat and power demand calculations, the interpretation of the CHP plant, and comparison of alternative heating systems. Based on the simulation of the hourly operating data over one year, all relevant results for heat and electricity, cost and recoverable revenue, energy balance and emissions are calculated for separate and combined production. In addition, the program includes a complete reporting system, with all the results, tables and graphics. The program interface is shown in the Figure below.

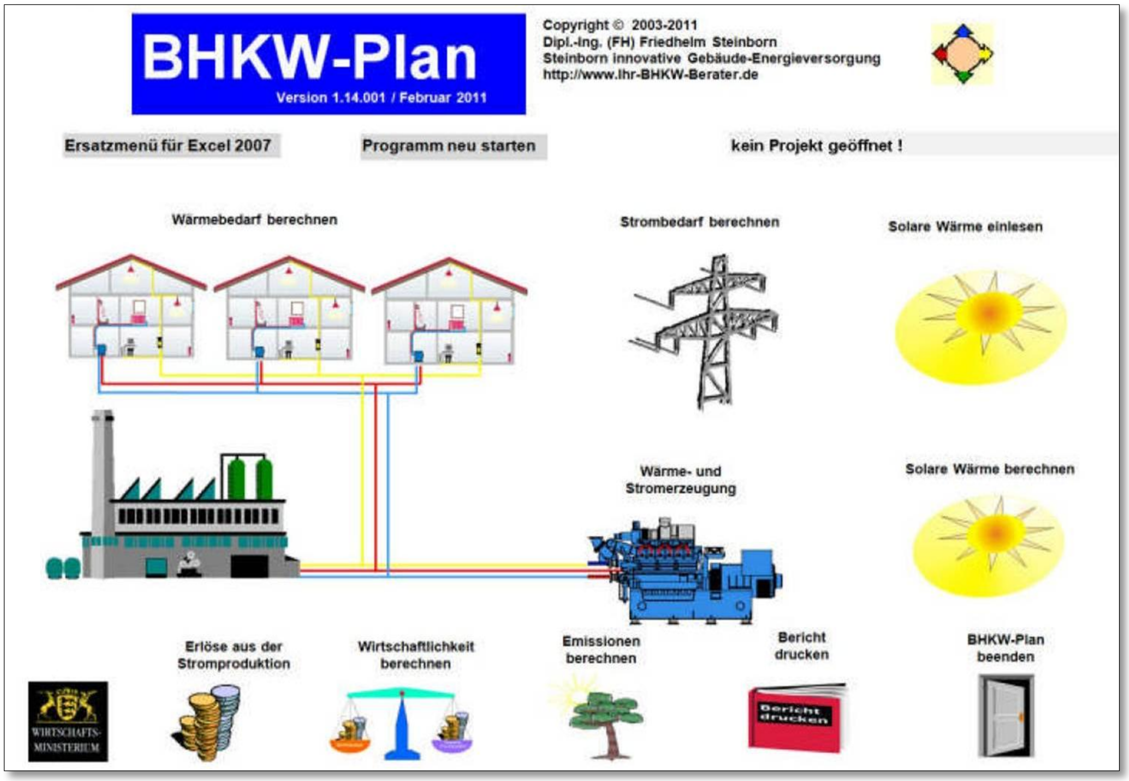

Figure 34 BHKW Plan Program

Evaluation of CHP calculation software: BHKW Plan

Because BHKW Plan is not a worldwide known program, an evaluation is made in this chapter to explain the handling of the program, as well as its pros and cons.

The difficulty encountered in the planning of combined heat and power is to create a proper annual heat and electricity demand curve, where empirical data and estimates are often applied. In addition, an hourly accounting of electricity and heat requirements is almost impossible without computer assistance. Here are the major benefits of simulation software.

The heat and power requirements can either be simulated by building modeling, an extensive database of consumers (e.g. buildings, process heat, and electricity consumers). A variety of building types, process types and current consumer types is available to determine the hourly load curves. On the other hand, it is also possible to integrate hourly data as a file, e.g.

existing data from an older building or, as in this case, a different program is used to simulate heating and cooling loads. This flexibility is a plus for the software.

The CHP module and boiler database has a lot of choices with different performance data and fuels. There is a possibility to edit or re-create CHP and boiler units, where new created data bases require very specific vendor information. The selection of an operating mode and a CHP module, together with a buffer memory and a peak boiler, allows a number of possible combinations. However, a disadvantage is that a power-oriented operation is not possible, if the heating and cooling loads are uploaded from a separate file. The company Steinborn Innovative Building Energy Supply was contacted and is currently working on that issue. However, the hourly simulation of heat and power production and the associated adjustment to the hourly demand is certainly the main strength of the program. Another disadvantage is the relatively rigid concept of the operating mode. There is no possibility to vary the schedule when the CHP module shall operate or not, or to change operation mode within a year. Furthermore, it is important to note that the program does not provide suggestions for the selection of a cogeneration plant, which meets the thermal and electrical energy situation best. It does not offer optimization calculations; this remains the task of the planner to select a fitting CHP module even with the help of the subsequent economic analysis. However, due to the component data base a fairly rapid comparison can be achieved.

The economic analysis of the program proved to be circuitous. This has several reasons: First, the breakdown of capital costs was very detailed. The program also includes the taxation of electrical energy, in terms of the fuel tax refund, the registration of grants, and funding schemes designed to German standards and regulations. Overall, to achieve the required ratio of the results, a relatively large effort is necessary to determine the data that are needed for the economic calculation, especially to adjust it to U.S. regulations. Second, the economic analysis can only compare CHP systems consisting of a power supply system designed from a boiler and electricity supplied by the grid. The influence of reducing the acquisition or energy cost cannot be calculated by the program. It only calculates the economic situation based on the cost data, which have been put into the system.

The program is not suitable for interpretation by the CHP for stand-alone operation. Although it is possible to simulate a power controlled operation and thus coverage of the entire electrical energy needs by the CHP, the stand alone system operating with a required battery backup system cannot be taken into account.

Another advantage is the possibility of solar system integration in the calculation. In this case study, this aspect was not investigated, so that no detailed analysis about the ease of application can be made.

In summary, the BHKW Plan software can be described as a very useful tool that can be of great help for technicians, in the design of systems. The complexity of a CHP design requires an intensive analysis of the program itself and the underlying theory. However, the application itself is much more persuasive than other simulation programs such as TRNSYS. Furthermore, it should be noted that the program is currently only available in German on the market. A translation for an international version needs to be discussed with the owner.

APPENDIX E

MONTHLY BALANCE OF HEAT AND ELECTRICITY GENERATION

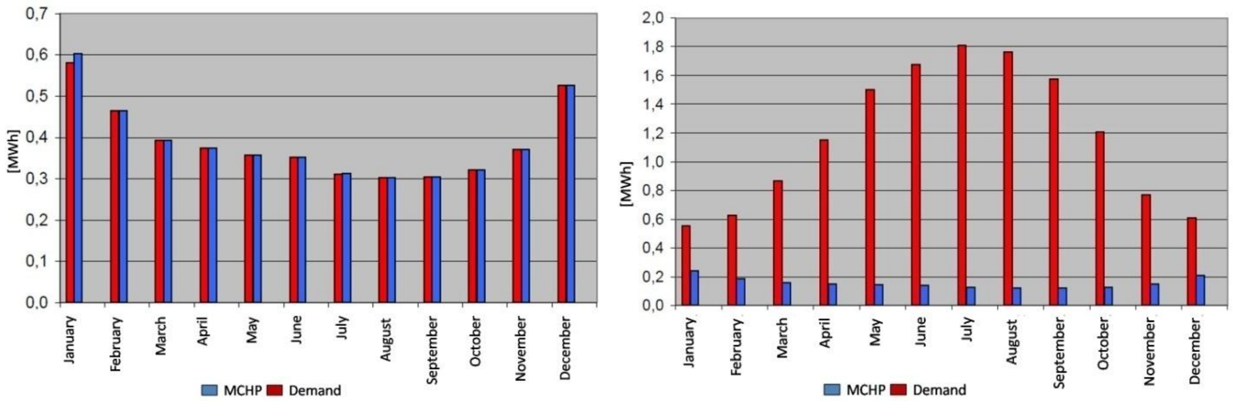

Figure 35 Heat and Electricity Results: Atlanta - Otto Engine

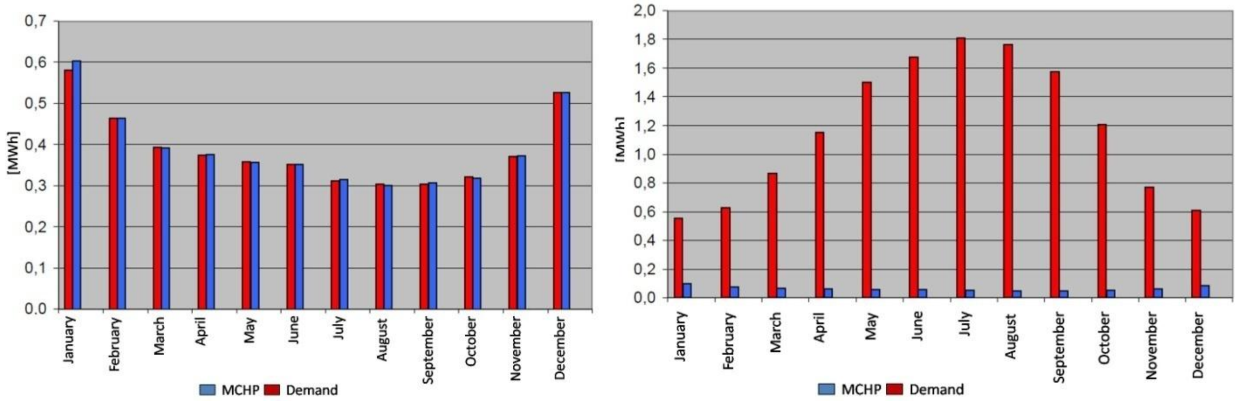

Figure 36 Heat and Electricity Results: Atlanta - Stirling Engine

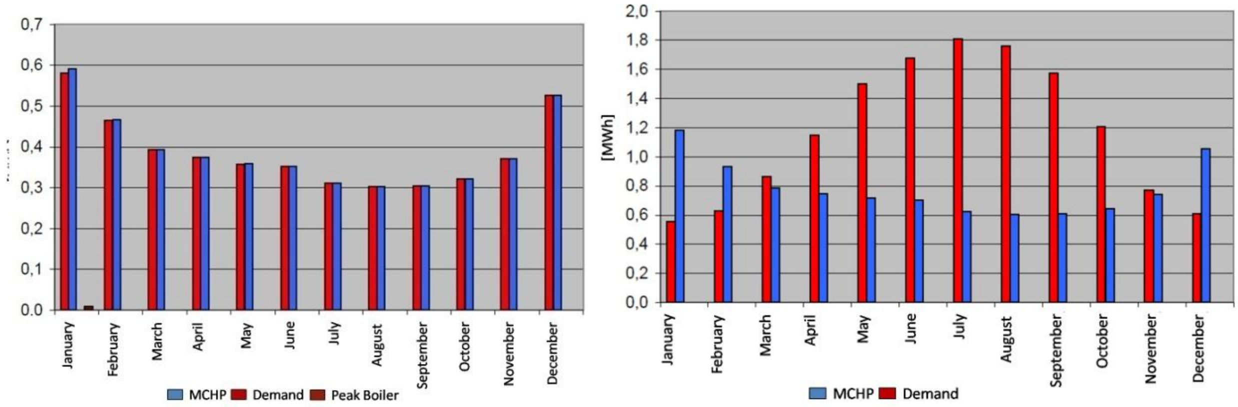

Figure 37 Heat and Electricity Results: Atlanta - Fuel Cell

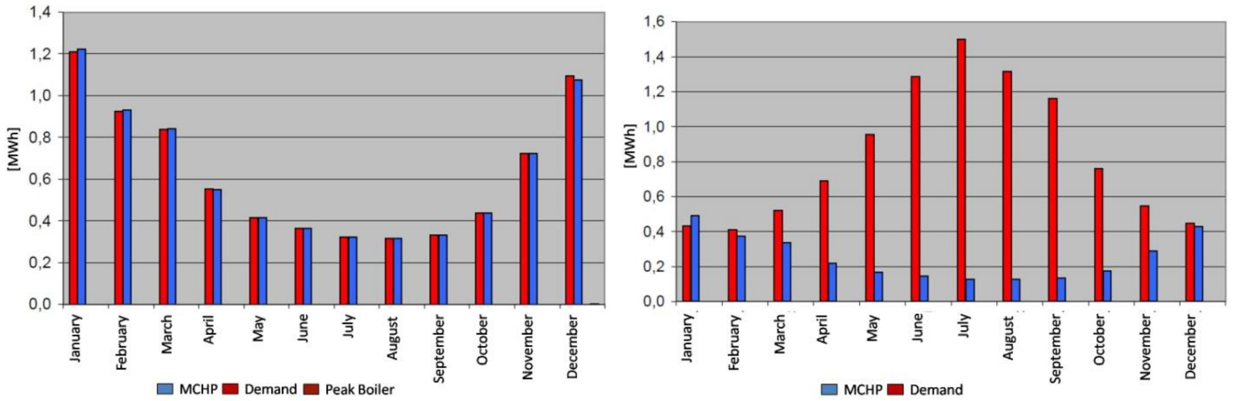

Figure 38 Heat and Electricity Results: Chicago - Otto Engine

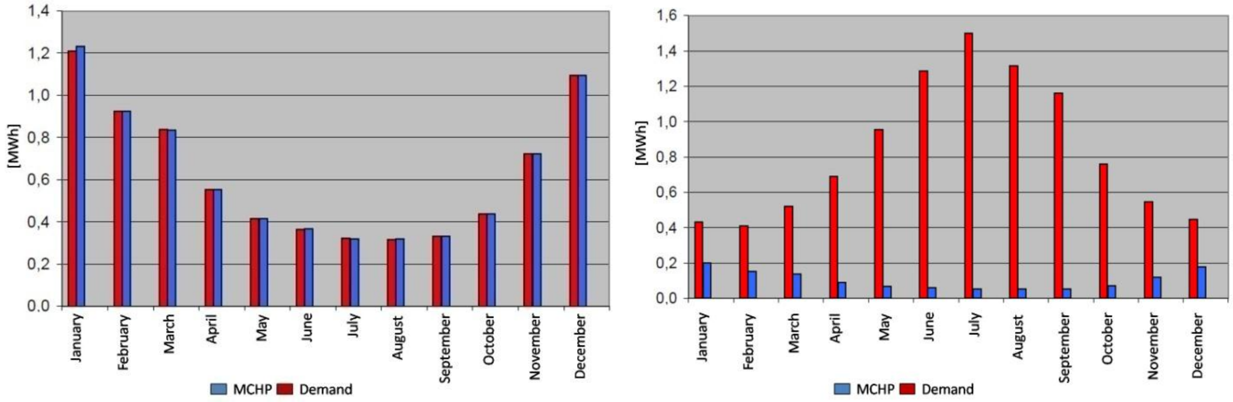

Figure 39 Heat and Electricity Results: Chicago - Stirling Engine

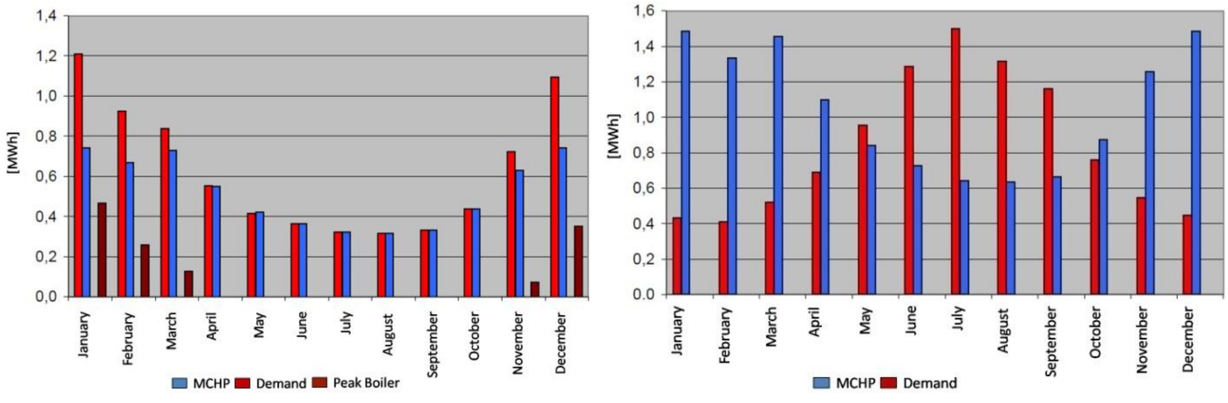

Figure 40 Heat and Electricity Results: Chicago - Fuel Cell

APPENDIX F

FUEL BALANCE: SEPARATE AND COMBINED HEAT AND POWER GENERATION

Table 33 Fuel Balance: Separate and Combined Heat and Power Generation – Atlanta

Variant		Atlanta Otto Engine	Atlanta Stirling Engine	Atlanta Fuel Cell
Micro - CHP	[MWh/a]	7.1	5.9	16.5
Peak Boiler	[MWh/a]	0	0	0
Sum	[MWh/a]	7.1	5.9	16.5
Boiler	[MWh/a]	5.7	5.7	5.7
Power plant	[MWh/a]	5.2	2.1	25.8
Sum	[MWh/a]	10.9	7.8	31.5
Savings	[MWh/a]	3.8	1.9	15

Table 34 Fuel balance: Separate and Combined Heat and Power Generation – Chicago

Variant		Chicago Otto Engine	Chicago Stirling Engine	Chicago Fuel Cell
Micro - CHP	[MWh/a]	11.5	9.6	22.1
Peak Boiler	[MWh/a]	0	0	2
Sum	[MWh/a]	11.5	9.6	24.1
Boiler	[MWh/a]	8.7	8.7	8.7
Power plant	[MWh/a]	8.3	3.4	34.5
Sum	[MWh/a]	17	12.1	43.2
Savings	[MWh/a]	5.5	2.5	19.1

APPENDIX G

COST PROGRESSION OF CHP UNITS

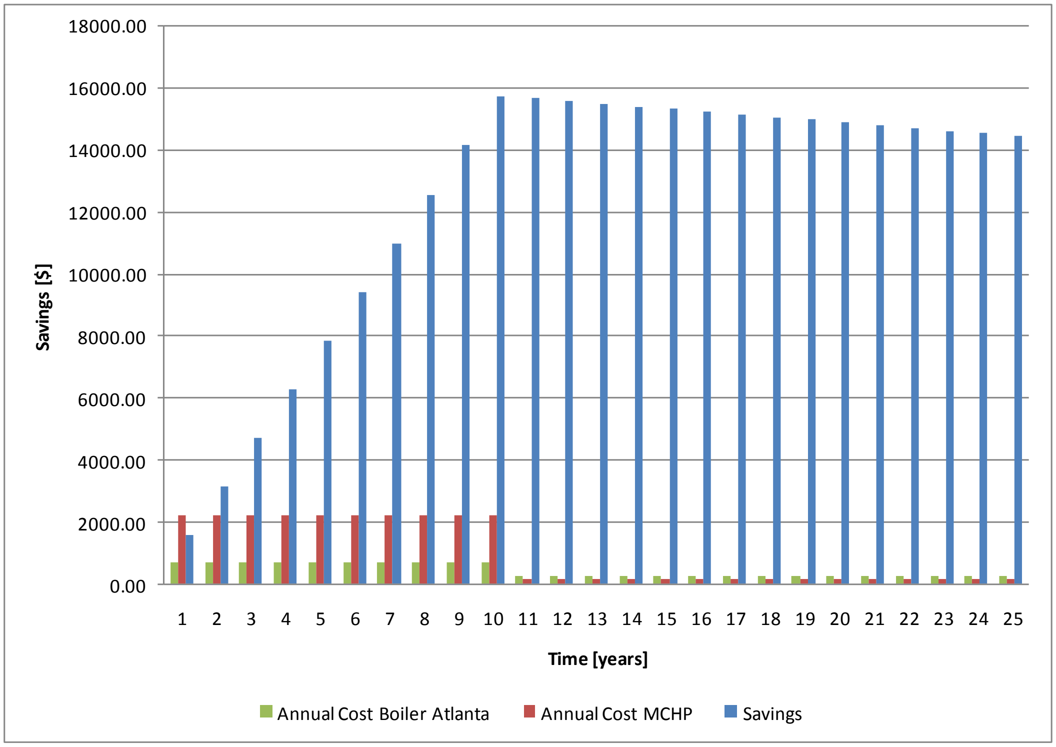

Figure 41 Economic Calculation Atlanta - Otto Engine

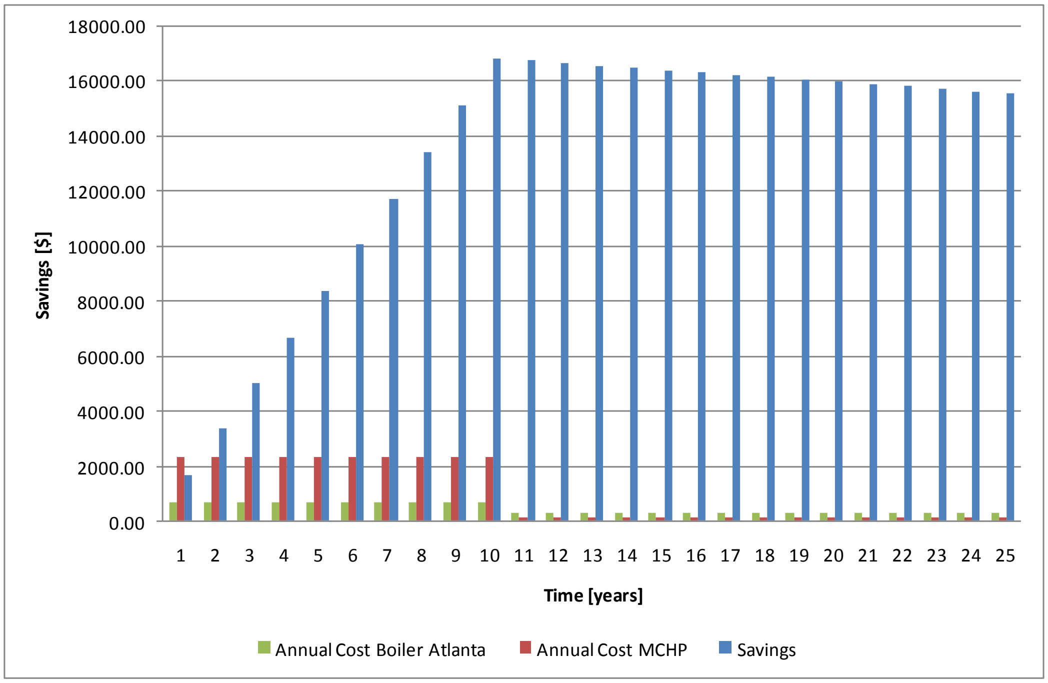

Figure 42 Economic Calculation Atlanta - Stirling Engine

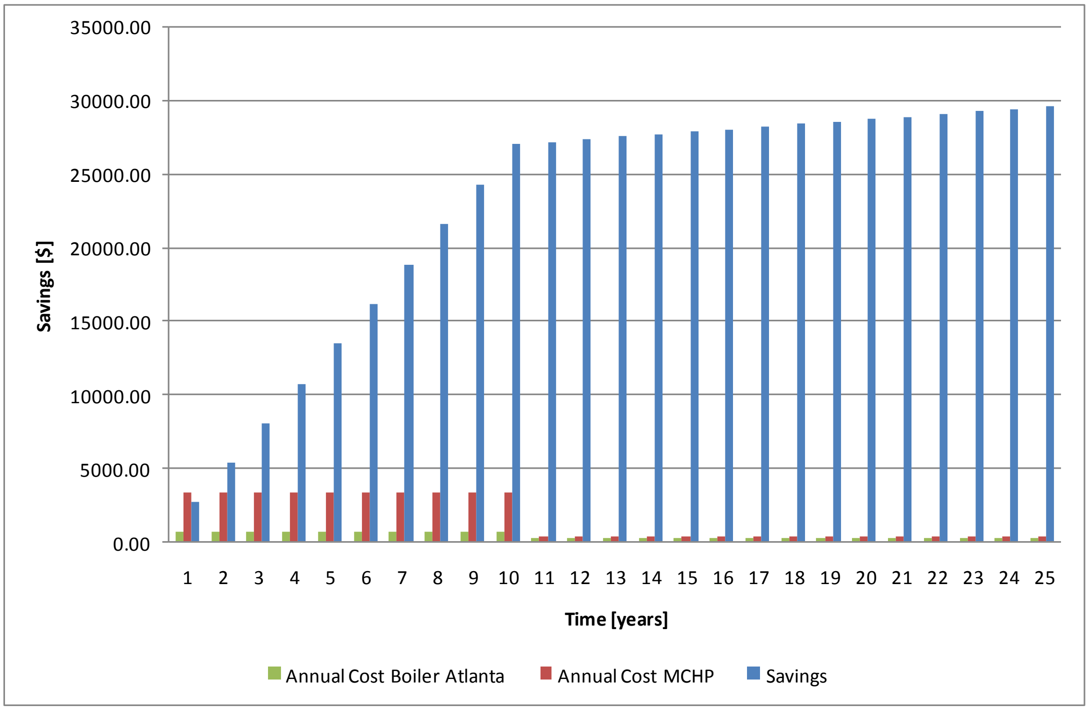

Figure 43 Economic Calculation Atlanta - Fuel Cell

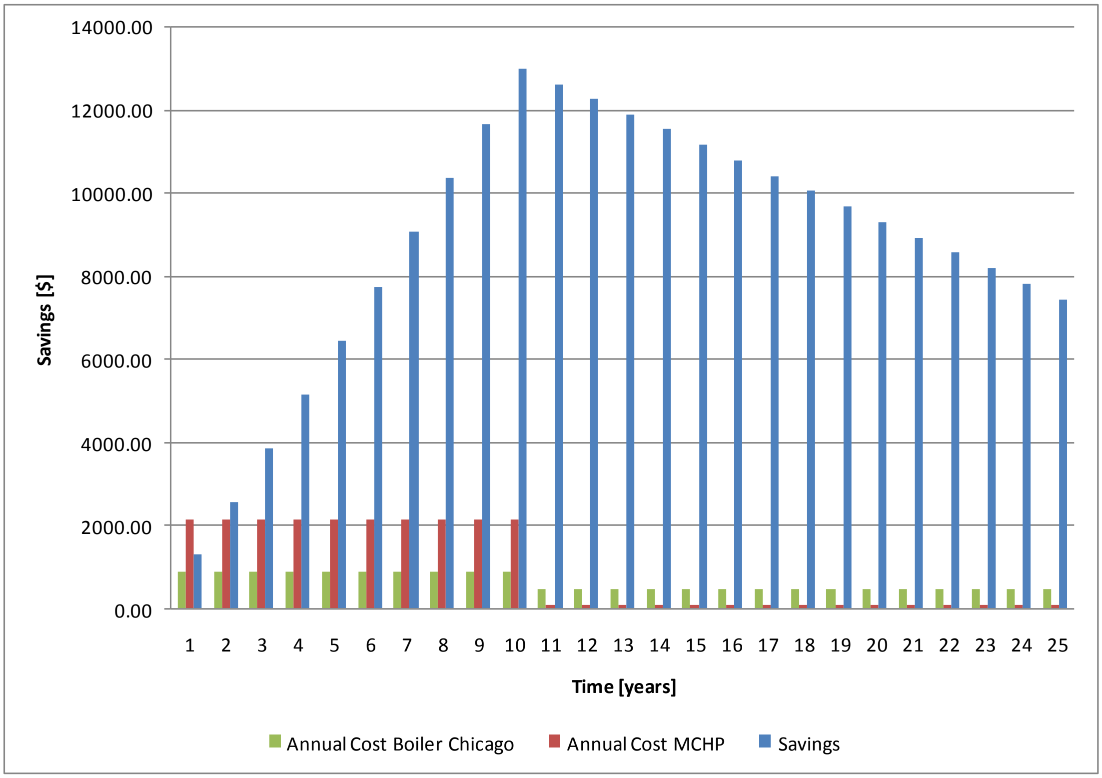

Figure 44 Economic Calculation Chicago - Otto Engine

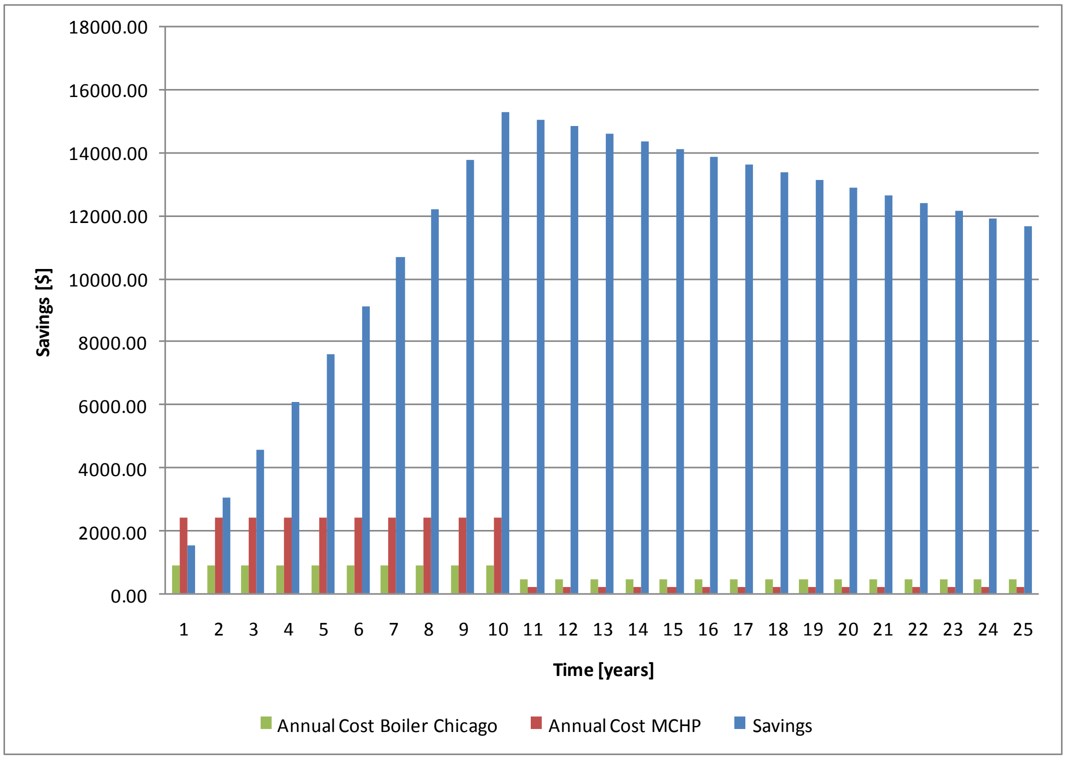

Figure 45 Economic Calculation Chicago - Stirling Engine

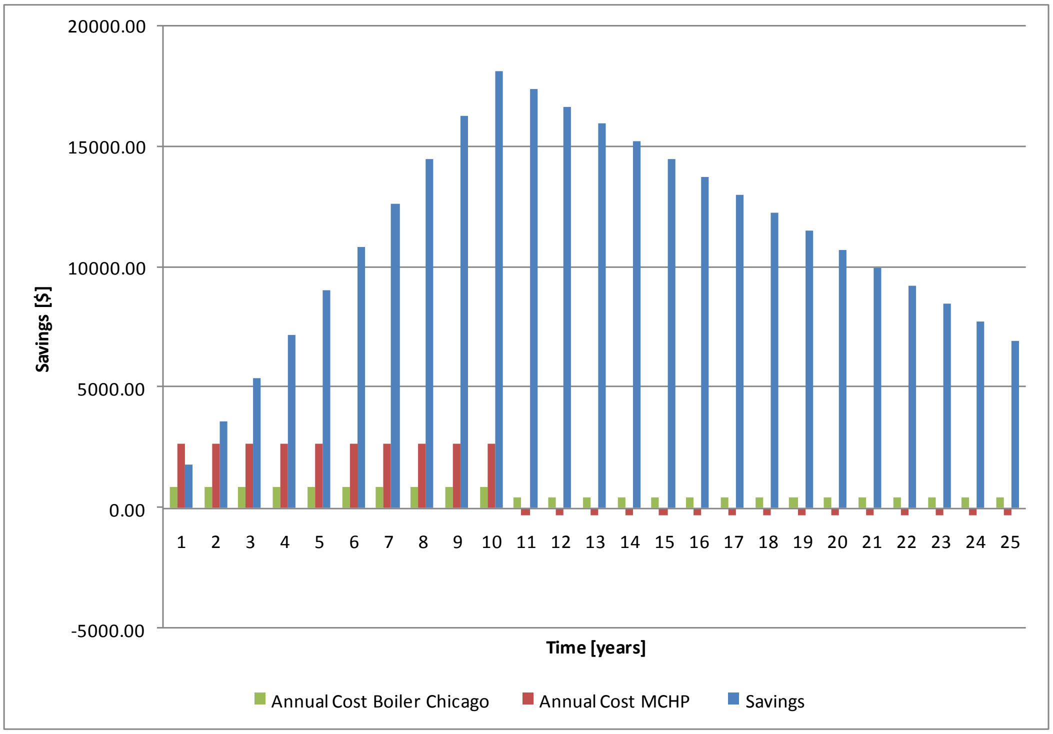

Figure 46 Economic Calculation Chicago - Fuel Cell

VITA

Nadine Reinert was born in Stadthagen, Germany, as second of two children. She attended the Wilhelm-Busch-Gymnasium in Stadthagen, Germany. After Graduation, she went to the University of Applied Science and Arts in Hannover and worked at the same time for the Joh. Heinr. Bornemann GmbH as draftsman. When she received her Diplom, she took over a position as design engineer for the same company. After one and a half years she got promoted to the system engineering department. In 2010, she relocated with her husband to the USA and started the Graduate Program in Mechanical Engineering at the University of Tennessee at Chattanooga. During that time she accepted a graduate assistant program at UTC. Nadine is currently working in the Environmental Department of Volkswagen Group of America, Chattanooga Operations, LLC.