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PERFORMANCE ANALYSIS OF A MICROTURBINE AT VARYING OPERATING CONDITIONS

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ABSTRACT

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Performance analysis of a microturbine at varying operating conditions

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There is a growing trend towards decentralized heat and electricity generation. Micro combined heat and power (micro-CHP) plants have been recognized by the European Union as having high potential to improve energy efficiency and reduce carbon dioxide emissions. The performance of CHP with the microturbine as a prime mover is studied in this thesis. Special attention is given to the operation using biofuel, as the share of renewable energy for heat and power generation is projected to grow in years ahead. Fuel properties, characteristics of the CHP with microturbine and current situation in European energy sector are studied through a comprehensive literature review.

In the work, a steady-state model is used that has been developed for the microturbine with heat balance modeling software IPSEpro. Component-specific compressor and turbine maps are applied in the model. The main objective of this thesis is to provide information about the microturbine Turbec T100 performance at varying operating conditions, such as fuel composition, rotational speed, turbine inlet temperature and ambient temperature on the basis of the IPSEpro model.

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman letters

LHV	lower heating value	[kJ kg^{-1}]
N	rotational speed	[rpm]
P	power	[kW]
T	temperature	[K]
TIT	turbine inlet temperature	[K]
a	corrected mass flow at pressure ratio zero	[m s $K^{-0,5}$]
b	pressure ratio at zero mass flow	[-]
h	enthalpy	[kJ kg^{-1}]
$\dot{m}$	mass flow rate	[kg s^{-1}]
p	pressure	[Pa]
x	x-axis	[-]
y	y-axis	[-]
z	curvature of the curve	[-]

Greek letters

Φ	heat output	[kW]
ε	recuperation ratio	[-]
η	efficiency	[-]
π	pressure ratio	[-]
ϕ	corrected speed	[rpm $K^{-0,5}$]
χ	corrected mass flow	[m s $K^{-0,5}$]

Subscripts

air	air
c	compressor

dh	district heating
e	net electric
exh	exhaust gas
f	fuel
g	generator
in	inlet
m	fuel gas compressor motor
out	outlet
t	turbine
tot	total

Acronyms

AC	Alternating Current
CHP	Combined Heat and Power
DC	Direct Current
DG	Distributed Generation
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	European Union
ETS	EU Emissions Trading System
GHG	Greenhouse Gases
HHV	Higher Heating Value
IEM	Internal Electricity Market
ISO	International Organization for Standardization
LHV	Lower Heating Value
MDK	Model Development Kit
PSE	Process Simulation Environment
RES	Renewable Energy Sources
rpm	revolutions per minute

1 INTRODUCTION

This thesis discusses the performance of a combined heat and power plant with microturbine as a prime mover. In the work, a steady-state model is used that has been constructed for the microturbine using heat balance modeling software IPSEpro. The main objective of this thesis is to provide information about the microturbine Turbec T100 (currently AE-T100 from Ansaldo Energia) performance at varying operating conditions, such as fuel composition, rotational speed, turbine inlet temperature and ambient temperature on the basis of the IPSEpro model.

1.1 Background of the study

Over the last several decades, the energy resource demand has increased significantly due to the technological and industrial growth attended by huge population development. There is a growing trend towards decentralized power and heat generation all over the world. Modern energy environment is transforming quickly as governments try to reach cost-efficient use of available resources by enabling the development of low carbon economy. The overarching targets of the European energy strategy are to increase the use of renewable energy sources, to provide a security of supply and to reduce carbon dioxide emissions. (Badea 2015)

Along with raising decentralization of heat and electricity generation, renewable energy sources (RES) are gaining interest. The share of heat and power derived from renewables has grown significantly over the past decade. The energy produced from RES accounted for almost 16 percent of total European energy consumption in 2014 and it is expected to grow. (Lins et al. 2015) The utilization of RES has many advantages, including mitigation of greenhouse gas (GHG) emissions, decreasing the EU energy dependence on fossil fuel imports, as well as increasing competitiveness and export potential. The growth of renewables can also promote the employment in Europe, through the creation of new workplaces. Bioenergy is the largest RES in the European Union, also it is the preferred fuel for combined heat and power (CHP) production. The use of biomass in CHP plants is beneficial from environmental, social, and economic viewpoints. This provides a strong interest to further performance improvement and wide implementation of CHP units. (European Biomass Association 2016)

The buildings and residential sector contribute to a large share of energy demand, and micro-combined heat and power, or micro-CHP, has proven to be a successful way to cover heat and power needs for buildings and dwellings. CHP plants combine on-site electricity production with the use of byproduct heat. Taking advantage of the decentralized energy production, micro-CHP systems are a potential substitute to the central generation stations, particularly in remote locations. These systems are typically used in private homes, farms or small commercial applications. For instance, in Germany farmers operate about 90 percent of the biogas plants. (Wiesheu 2016)

The European Union has recognized micro-CHP systems as having an essentially advantageous role in upgrading energy efficiency. Micro cogeneration promotes European energy and social policy targets, including competitive ability and sustainability of energy delivery, decentralization, and security of supply, minimizing of distribution energy losses. Micro-CHP is a small-scale form of CHP with installed capacity ranging from 30 kW to 250 kW electricity. (Darrow et al. 2015) However, in the EU Energy Efficiency Directive, the term “micro-cogeneration unit” is defined as a unit with a capacity less than 50 kW electricity, but in this thesis, the term “micro” is used for larger units too. (European Comission 2012)

Common technologies used in the micro-CHP are reciprocating engines, turbines using steam or organic fluid, gas turbines, fuel cells, Stirling engines, and microturbines. In this thesis, a CHP plant with microturbine as a prime mover is studied. The microturbine is a compact, radial flow gas turbine. Today microturbines are one of the most widely-used power generating technologies and they are predicted to have sustained growth in future decentralized generation in remote areas, for example in domestic applications and small industry. (Opdyke et al. 2004) These units produce heat and electricity from the same energy source in situ. The electrical efficiencies of the microturbines are slightly lower than similarly sized reciprocating engines. Nevertheless, due to their simple design and relatively few moving parts, microturbine generators have the potential for simpler assembling, longer working time, lower noise and vibration levels, and simpler service requirements. In addition, microturbines have significantly lower capital costs and emissions than the reciprocating engines. The economics of microturbine generation are increased by continuous baseload operation of the unit and the efficient usage of the thermal energy included in the hot exhaust. Usually, heat is recovered as a hot water or low-pressure steam, also exhaust gas is suited for heating or drying processes or for driving the thermally activated equipment, for example, absorption chillers. (Goldstein 2003)

The majority of the current energy demands are covered through the combustion of fossil fuels, such as natural gas, oil, and coal. However, the utilization of fossil fuel is expected to decrease in the coming decades, because of the new emissions policy, depletion of fossil fuels reserves and the necessity of sustainable energy systems. (Ghenai 2014) Traditionally microturbines have been designed for utilizing natural gas as a primary fuel. However, they can operate on a wide variety of fuels, including distillate oil, liquefied petroleum gas, sour gas, biogas, industrial waste gases and manufactured gases. (Goldstein 2003)

In this thesis, three kinds of fuels with the different chemical composition are investigated: natural gas, biogas from anaerobic digestion and landfill gas. Natural gas is used as a traditional fuel for the microturbine and renewable fuels as the possible alternatives to conventional fuel. During recent years, the number of biogas plants in Europe has increased significantly with a total of 17 240 in 2015. According to the European Biogas Association data, 63 percent of these plants are located in Germany. Germany can be considered as the undisputed world market leader in the biogas production and distribution. Biogas production is one of the prime movers of economic growth in this country. A positive trend can be seen in central Europe where the number of biogas plants has increased in the recent years. Most of the biogas plants operating in Europe utilize agriculture feedstocks (68 percent), followed by sewage (16 percent), and the future trend in Europe is the increasing growth of the number of agriculture biogas plants. (European Biogas Association Report 2015) This is the reason, why biogas from anaerobic digestion is discussed as a possible renewable fuel for the microturbine in this thesis.

The second type of renewable fuel used in this work is landfill gas. This gas is produced during the anaerobic decomposition of organic matters in municipal solid waste. In recent years, a lot of plants for extraction and utilization of landfill gas have been built, and this technology is widely used in the world. The leaders in landfill gas use in Europe are the Balkan Peninsula and Turkey, in these regions large share of municipal solid wastes is disposed in landfills. Extraction of landfill gas helps to reduce the methane emissions from landfills into the atmosphere. Moreover, it replaces fossil fuels such as oil, coal, and natural gas. (Dace 2015) Despite the fact that landfill gas has a lower methane content than biogas from anaerobic digestion, it is widely used for energy production and it is also discussed in this thesis.

Microturbines can be used in connection with biogas production. The microturbine utilizing renewable fuel requires biogas from anaerobic digestion (AD), landfill gas, or a biomass gasifier to generate gasification gas for the turbine operation. For microturbine run on biogas, the additional equipment is required for the gas cleaning. The cleaning includes removal of sulfur compounds, additional moisture, and siloxanes. It is needed to prevent the corrosion and damage in the blades of the microturbine. The utilization of biogas increases the costs for fuel cleaning and maintenance of the unit comparing to the natural gas utilization. Microturbines have proved that they can operate on renewable gaseous fuels reasonably well due to their simple design. While operating on the landfill gas or biogas from AD, there is a small reduction in net electric power output, approximately 10 to 15 percent, due to the additional power needed for the fuel gas compressor. Considering this and gas cleaning, the price per kW increases from 15 to 25 percent for the units operating on landfill gas or biogas from AD, compared to the price for the same size units utilizing natural gas. Maintenance costs also raise from 30 to 40 percent, because of more frequent intervals. (U. S. Environmental Protection Agency 2007)

1.2 Objectives and methods

The main objective of this thesis is to provide information about the steady-state performance of the microturbine at varying operating conditions, such as fuel composition, rotational speed, turbine inlet temperature and ambient temperature on the basis of an IPSEpro model. This work is concentrated on the processes that take place during operation in the commercially available microturbine Turbec T100 (currently AE-T100 from Ansaldo Energia). The practical part contains three simulations. Fuel properties, as well as characteristics of the CHP with microturbine and current situation in European energy sector are studied through a comprehensive literature review.

The model of the microturbine has been constructed in IPSEpro software with a reasonable degree of complexity. However, some simplifications have been made that relate to the internal flows and heat losses of the engine, the power need of the auxiliary systems, and the combustion process. The model can be used for simulating varying operating conditions of the similar microturbine units.

1.3 Outline of the thesis

This thesis is outlined as follows:

Chapter 2 introduces the current situation in European energy sector with a focus on the micro-cogeneration technologies and their increasing importance for mitigating the climate change.

Chapter 3 discusses the basic components of a micro-cogeneration plant and its economics, also this chapter discusses the commercially available microturbine Turbec T100.

Chapter 4 provides information about the usage of biogas from anaerobic digestion and landfill gas, their advantages and support schemes for future development in the European Union. Gaseous fuel characteristics used in the simulations are discussed.

In **chapter 5**, description of IPSEpro heat balance modeling software is given. The microturbine model is described at design point operation as well as outside design conditions. Special attention is given to the use of component-specific compressor and turbine maps in the model.

Chapter 6 includes results of IPSEpro model simulations.

Chapter 7 provides conclusions and summary of the thesis and suggestions for the future research.

2 MICRO COGENERATION IN THE EUROPEAN UNION

In this chapter, the general outlook on micro combined heat and power generation is presented, including current situation and challenges in European energy sector. It provides information about modern European policies, regulatory frameworks, and trends, promoting wide implementation of micro-CHP technologies for heat and power generation.

2.1 The European energy sector

From a political perspective, the European Union is an admirable example in relations between its states. Previously, the energy sector was an exclusive authority of the state, but with its rising importance, at present time it has transformed to a shared competence among the European Union and the Member States which must be satisfied. Thus, energy sector development is a shared competence with a sustainable regulatory environment. Consequently, the European Union targets at supporting the energy market operation and providing security of supply, encourage energy efficiency, power economy, and renewable energy sources. However, the Member States are relatively free to determine the way in which their energy sources are used. (Badea 2015)

From a technical viewpoint, The European energy system has “provided the vital links between electricity producers and consumers with great success for many decades” (Potocnik 2006). The European Union has begun to proceed from the current centralized energy production from fossil fuels and nuclear power plants to innovative, decentralized energy production from small-scale systems utilizing renewable energy sources, with low carbon emission technologies such as the microgeneration power plants. These innovations assume a conversion in consumer’s energy behavior from the traditional passive to new active role. Consumers turn into individual energy producers. (Badea 2015)

In European Union the modern intelligent generation of grids, Smart grids, are described as “electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies” (Potocnik 2006). This implies that Smart Grids comprise the entire electricity generation and consumption chain with import and export of energy and current situation on the electricity market. Under the conditions where the Member States are switching to Smart Grid, modern low-carbon systems such as micro-cogeneration technologies are especially important. The successful implementation of Smart Grids is strongly influenced by wide attainment of micro-cogeneration units by domestic customers and small/medium-sized concerns. Micro-cogeneration systems are a kind of decentralized energy production used in small-scale heat and power generation by individual producers, small and medium enterprises to cover their own energy demand as alternates or additions to traditional centralized grids. These systems can utilize fossil fuels, renewable energy sources or their combination to produce heat and power. (Badea et al. 2013)

2.2 Challenges

To have a full understanding of the role and growing significance of micro-cogeneration technologies within the modern context, it is necessary to have a look into the current challenges in the European energy sector. The European Union has to mitigate the environmental challenges on climate change from greenhouse gas emissions, guarantee the security of supply by becoming an independent energy producer, and improve the infrastructure for the European grids to protect energy sector from possible energy cut-offs. Decreasing GHG emissions is an essential aim as they are the main reason for climate changes and air pollution. The main polluting component of GHG is carbon dioxide. In a global context, the European share of the total GHG emissions is about 11 percent. According to the international agreements, such as Kyoto Protocol, and European policies, reducing GHG emissions is evident to improve the environment. Utilizing full potential of RES is an opportunity to decrease GHG emissions and the European Union makes a shift to increase the RES usage in energy generation. As a consequence, the implementation of micro-CHP systems has a fundamental position in decreasing GHG emissions. (Badea et al. 2013)

Taking into account these environmental challenges, the biggest energy goal for the European Union is providing security of supply (European Commission 2011). In Europe, the energy demand is slowly but confidently rising. Since the primary energy sources cannot fully cover the increasing energy demands, Europe has to import energy from other countries. The International Energy Agency describes energy security as the “uninterrupted availability of energy sources at an affordable price” in order to protect from possible cut-offs. For providing easily accessible and effective energy sources there are several key elements that should be developed, and micro-cogeneration units have a certain role. First of all, the European Union must develop a well-balanced power supply system with a variety of generation technologies. It is also known as energy mix, it includes a combination of sources utilized to generate energy anywhere anytime. Under these conditions, micro-cogeneration systems can be a profitable and reliable alternative to fossil fuel substitution. (Badea et al. 2013)

Relating to power delivery, the key element in providing security of supply and flexibility of the energy network is having acceptable transmission lines and interconnection systems to transport available energy easily. This especially applies to users of micro-CHP units as they need proper network access to export the energy surplus. Another key element to providing security of supply is maintaining the high quality of energy. In terms of high-performance transmission, this can indicate the shift to decentralized energy production. And this transition also covers micro-cogeneration systems, because they are on the basis of decentralized energy production. Improvements in technologies are essential to becoming highly efficient in generating more energy with fewer resources and having less GHG emissions. Among modern highly effective technologies, micro-CHP units are known as latest technologies on micro cogeneration. Moreover, modern technologies directly help to improve the environment situation with decreasing harmful emissions. (Badea et al. 2013)

The last concern in providing the energy security and relating to high efficiency operation is energy savings. The above-mentioned issues are connected with increasing energy demand, this concern highlights ways of energy savings. Energy savings can be achieved through improving energy efficiency. This implies using less energy or decreasing energy losses to meet the same demands. In the household and commercial sectors, energy is mostly used by domestic buildings as they constitute about 75 percent of the total building floorage. Wide implementation of micro-cogeneration systems in these sectors can be beneficial in both providing the energy security and mitigating the climate changes. (Badea et al. 2013)

2.3 Policy overview

For overcoming all these challenges and concerns, The European Union has developed a new competitive energy policy for switching to commercially viable, sustainable, and secure energy across the European Union. In order to achieve this, Europe has implemented several documents, such as 2020 Climate and Energy Package and 2030 Framework for Climate and Energy Policies, all under a long-term Roadmap for moving to a low-carbon economy in 2050. All these policies complement and give a support to one another. Beginning with 2020 Climate and Energy Package, the following policies rely on previous results, consolidate and upgrade one another. (European Commission 2010)

Europe 2020 is a complex approach for the period from 2010 to 2020 targeted at providing smart and sustainable growth. It is applied across economic, social and energy issues and establishes the following three key objectives to be gained by 2020:

- Reduction of GHG emissions at least by 20 percent compared to 1990,
- Increasing the share of renewables in EU energy production by 20 percent,
- Reduction of primary energy use by 20 percent by means of increasing energy efficiency. (Badea et al. 2013)

There is a number of key points in the European Union energy policy related to micro-cogeneration systems. These systems directly cover providing energy security by improving energy efficiency and consumers' empowerment. The European Union has a huge energy saving capacity from buildings, again it is directly connected with micro-cogeneration systems. Moreover, micro-CHP systems also promote improving energy efficiency within the energy producers and end-users by using RES for generating heat and electricity. (Badea et al. 2013)

The Energy Roadmap 2050 is a guideline to the decarbonization of the European Union. Its aim is to reduce the GHG emissions at least by 80 percent below 1990 level by 2050. The strategy of decarbonization of economy is closely connected to micro-cogeneration systems as clean technologies are necessary for the Europe to cut its GHG emissions. Improving energy efficiency is a key element in this shift. Thus, innovations and investments in micro-

CHP technologies and low-carbon energy production are essential. This means a much greater demand for renewable energy sources and locally produced energy. The Roadmap also provides intermediate objectives on the way towards to at least 80 percent GHG emissions reduction, 40 percent by 2030 and 60 percent by 2040. The next step of European energy policies is the establishing of a framework for 2030. (Badea et al. 2013)

The 2030 framework for climate and energy policy has been created to maintaining competitive and sustainable energy goals in the European Union. The target of the framework is building a competitive and secure energy system which provides accessible energy for all consumers, increasing the security of supplies, reducing dependence on energy imports and creating new workplaces. Micro-cogeneration systems are also engaged in the transition to a competitive and sustainable economy. Improving energy efficiency is a necessary condition for decarbonization of economy and mitigation of climate changes. (Badea et al. 2013)

2.4 Regulatory framework

Taking into consideration main concerns for European energy sector, the concrete actions are implemented through the regulatory legal framework. The legislative framework for micro-cogeneration systems has had a constant growth during recent years. A brief description of European regulatory framework for micro-cogeneration systems is given below. The following directives are essential to understanding the connections between micro-cogeneration systems, users, and the Member States:

- Internal Electricity Market (IEM),
- Renewable Energy Sources (RES),
- Energy Performance of Buildings Directive (EPBD),
- Energy Efficiency Directive (EED). (Badea et al. 2013)

One of the main targets in European energy sector is the creation of internal energy market for providing options for all European consumers to choose between various energy supplying companies at reasonable tariffs and making the market open to all suppliers, primarily the smallest and those who invest in renewable energy. The Internal Electricity

Market Directive establishes the framework for competitive activities by creating general rules for the internal electricity market. This Directive creates market access for all energy consumers, including users of micro-cogeneration systems. The corresponding level of transparency is provided by the National Regulatory Authorities to give data on price levels for household customers covering prepayments, switching tariffs, disconnection tariffs, and payments for maintenance activities, covering also customer consumption data and considering complaints. Consequently, by establishing the common framework for the European internal electricity market, the IEM Directive deals with improving competitive ability of energy sector and encouraging active participation in the market of renewable energy suppliers. (Badea et al. 2013)

The RES Directive provides the common framework for the increasing energy generation from renewable energy sources in order to promote the European Union's goals. For this purpose, the Directive establishes national targets for the use of RES and supports all energy producers from RES in the electricity market. Moreover, the Directive recognizes the beneficial effects renewables have on local communities and end-users encouraging the implementation of decentralized energy systems. Micro-cogeneration systems are covered directly on two levels. Firstly, on the energy level, users of micro-cogeneration technologies make a profit from supporting schemes and simplified procedures when implementing small decentralized units. Secondly, on the information level, users of micro-cogeneration technologies make a profit from administrative costs and benefits for using RES. Consequently, the RES Directive promotes the implementation of decentralized renewable energy technologies, thus setting out the conditions for improving the security of supply while helping to achieve sustainable development with using RES. (Badea et al. 2013)

The Energy Performance of Buildings Directive focuses on improving energy efficiency in buildings, they must take part in decreasing GHG emissions and energy consumption. Micro-cogeneration systems are directly connected with both energy and information levels. On the energy level, users of micro-cogeneration systems have to decrease energy losses and must have energy performance certificates for buildings including permission for regular inspection of heating and air-conditioning systems. On the information level, this certificate should include all essential information with references for additional sources such as energy audits, material, and other support. Consequently, the EPBD Directive is an important step in mitigating the challenges in the European energy sector. (Badea et al. 2013)

The Energy Efficiency Directive is a comprehensive law book including also Efficiency in Buildings (EPBD Directive) and Efficiency in Products (equipment, lighting, energy labelling, and eco design). It sets 4 methods of operation: General measures promoting energy efficiency, Indicative national energy efficiency targets, Monitoring and reporting, and Fully sectored measures. It also efficiently integrates and covers a wide range of cogeneration technologies. (Bertoldi 2012) According to this Directive, micro-cogeneration systems are involved in energy use and energy supply. In the energy use, micro-cogeneration systems are connected both to public sector at national, regional and local levels, and to end-users, both domestic and industrial. In the energy supply sector, micro-cogeneration systems are connected to the grid by energy suppliers. In the public sector, government agencies have an important role and promote the implementation of micro-cogeneration technologies while making renovations to the buildings. In the private sector, users of micro-cogeneration systems, small- and medium-sized energy producers, have benefits from easy and fast organizational arrangements. Their connections to the grid are simplified as they can announce tenders. In the energy supply sector, the target for the national energy regulatory authorities is to ensure the modernization of the grid, installing smart grids and setting special network tariffs. Consequently, the EED Directive is a complex approach for providing the energy security by decreasing the primary energy consumption with improving energy efficiency. (Badea et al. 2013)

2.5 Trends

As it was stated in the previous chapters, renewable energy sources are the key element in a resolution of the European energy challenges: security of supply, mitigating climate changes, and competition issues. In order to find the solution for these issues in the European energy sector, the European Union has short-term and long-term targets and policies, Europe 2020 and Roadmap 2050 correspondingly. To give a summary of all the above, the tendency in the energy sector indicates that the use of renewables is increasingly encouraged. (Altmann et al. 2010)

Within RES, micro-cogeneration systems have a huge potential in solving all the energy challenges and making a positive contribution on multiple levels. These low-carbon systems are eco-friendly. They help to decrease the amount of GHG emissions and promote a sustainable future. The widespread implementation of micro-cogeneration technologies would imply a huge amount of new market participants, thus the competition in the internal energy market would increase. On this basis, micro-cogeneration systems are encouraged through the European energy policies. Figure 1 shows the relations between energy-related greenhouse gas emissions, the European Emissions Trading System (EU ETS), renewable energy sources, power generation and Distributed Generation (DG). Micro-CHP and small-scale generators have the central position among the distributed generation. (Altmann et al. 2010)

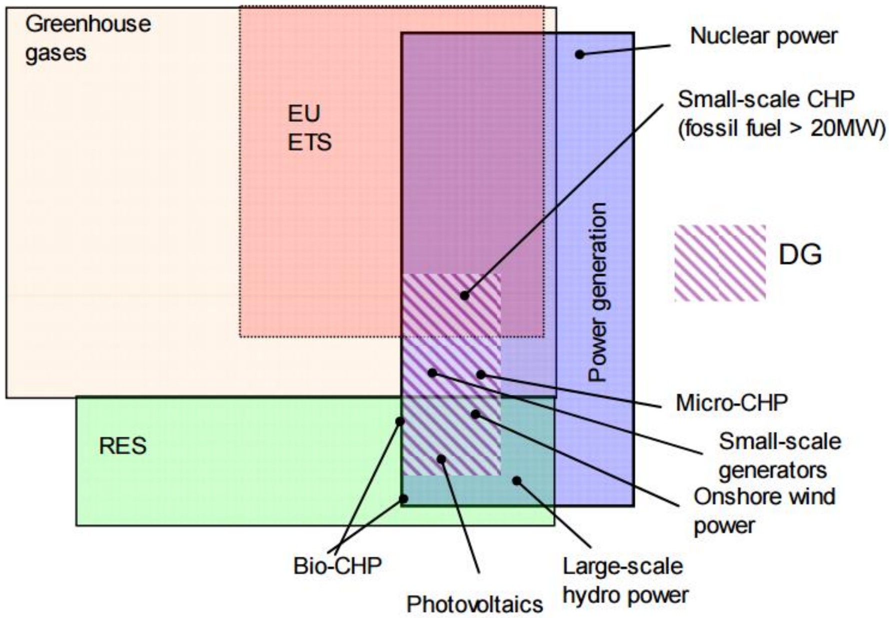

Figure 1. The position for micro-cogeneration systems in the European context (Altmann et al. 2010).

Furthermore, changes in consumers' behavior are supported by several incentives to make energy end-users more active and involved in the energy sector. Making connections between RES, micro-cogeneration systems and consumers leads to decentralized energy production. Cooperation of the microgrids of decentralized energy production leads to the important target of Smart Grids. These technologies have a high potential in solving current issues in the European energy sector and are engaged through European energy policies and realized through European legislation. (Altmann et al. 2010)

3 MICRO COGENERATION TECHNOLOGY

Combined heat and power (CHP) units produce electricity and heat from fuel combustion. In domestic sector, the term CHP refers to all electricity production systems that use recoverable waste heat for space heating and domestic hot water needs. Micro-CHP includes all systems ranging from 25 kW to 250 kW of electrical production. These systems are usually installed on single-family dwellings, small apartments, and offices. Generally, in the micro-cogeneration systems, power is produced on-site in a generation complex (prime mover and generator). The recoverable waste heat from the exhaust gas is used for water heating and for space heating needs. The heat utilization for heating purposes stimulates the increase of the energy usage from cogeneration units. (Badea et al. 2013)

3.1 Basic components and performance characteristics

Cogeneration systems are comprised of four basic parts: prime mover, electricity generator, waste heat recovery system and regulating system. The primary engine is an essential element, it is the basic component and, it determines the architecture of the cogeneration system. CHP units for domestic and commercial use can be divided in accordance to their prime mover and energy source applications. (Darrow et al. 2015)

Common technologies used in the micro-CHP are reciprocating engines, turbines using steam or organic fluid, gas turbines, fuel cells, Stirling engines, and microturbines. These technologies convert a portion of fuel energy to electricity, the amount of energy that is not converted, is released as heat. All these technologies, except the fuel cells, are known as heat engines, in which fuel is combusted. Fuel cells generate electricity from the fuel by a chemical reaction. (Darrow et al. 2015)

The operational parameters of different CHP technologies are presented in Table 1. The overall efficiency depends on a number of factors, such as working technology, types of fuel, operation point, a capacity of the unit, and also on the heat output. All these parameters are closely connected with the type of the mover installed in the cogeneration system. (Darrow et al. 2015)

Table 1. CHP technologies characteristics. Modified from (Darrow et al. 2015).

Performance parameters	Recipr. engines	Steam turbines	Gas turbines	Micro-turbines	Fuel cells
Electric efficiency [%], HHV	27 - 41	15 - 40	24 - 36	22 - 28	30 - 63
Overall CHP efficiency [%], HHV	77 - 80	near 80	66 - 71	63 - 70	55 - 80
Typical power to heat ratio [-]	0,5-1,2	0,07-0,1	0,6-1,1	0,5-0,7	1 - 2
Hours to overhauls, [10^3 h]	30-60	> 50	25-50	40-80	32-64
Availability [%]	96-98	72-99	93-96	98-99	> 95
Part-load	ok	ok	poor	ok	good
Start-up time	10 s	1 h – 1d	10 min – 1 h	60 s	3 h – 2 d
CHP installed costs [$ kW_e^{-1}]	1 500 – 2 900	670 – 1 100	1 200 – 3 300	2 500 – 4 300	5 000 – 6 500

Electric efficiency differs by technology and by size. Usually the larger is the unit, the higher is its electric efficiency. Overall CHP efficiency is one of the main characteristics of CHP. This parameter differs slightly among listed technologies. One of the main characteristics of CHP is that the more heat is wasted during electricity generation the more is an amount of heat that can be utilized for thermal processes. Thereby, the overall CHP efficiency depends on the heat quality and varies in the range from 65 to 80 percent. Availability shows the amount of time a unit can produce electric power and/or steam. It is usually determined in accordance with an operational environment of the unit. Start-up times vary greatly among given technologies. It can be seen, that reciprocating engines and microturbines have the shortest start-up time. Fuel cells and steam turbines have the longest start-up time, so these technologies are less favored for start-stop operations. (Darrow et al. 2015)

The use of microturbines has several benefits. They have few moving parts than other heat engines. Due to this, microturbines have a long operating period, design lifetime is estimated to be up to 80 000 hours with overhaul. Microturbines have a relatively compact size, in comparison with the power generated. These units are light-weighted and have a low noise and vibration level. Traditionally microturbines have been designed for utilizing natural gas as a primary fuel. However, they can operate on a wide variety of fuels. Microturbines have low emission levels and, therefore, this technology is gaining interest. That is why CHP with microturbine as a prime mover is investigated in this work. (Darrow et al. 2015)

Along with advantages, microturbine units have disadvantages, too. The major disadvantage of these systems is their low level of electrical efficiency. Under the conditions of increased altitude and ambient temperature, microturbines usually have reduction of power output and efficiency. Ambient temperature has a direct impact on microturbine performance. Efficiency is higher with colder ambient temperature. (Badea et al. 2013)

The microturbine is a compact, radial flow gas turbine. Cogeneration system with a simple gas turbine consists of the combined compressor-turbine package, generator, recuperator, combustor, and heat exchanger. These turbines are used to provide the useful mechanical work to produce electricity. Gas turbines with power output from 25 kW to 250 kW are usually called microturbines and they can be fuelled with natural gas, biogas, diesel, or petroleum. (Badea et al. 2013)

Microturbines and gas turbines are based on the similar Brayton cycle. This thermodynamic cycle operates with the following principle – air from the atmosphere is compressed, heated at constant pressure, and then expanded, yielding mechanical power surplus. In real microturbines and gas turbines, gases at high temperature and pressure, which are a result of the combustion of fuel mixed with compressed air, are expanded through the turbine. The power from the turbine is used to rotate the compressor and the generator. (Badea et al. 2013) A scheme of the basic components of a microturbine-based CHP system is illustrated in Figure 2.

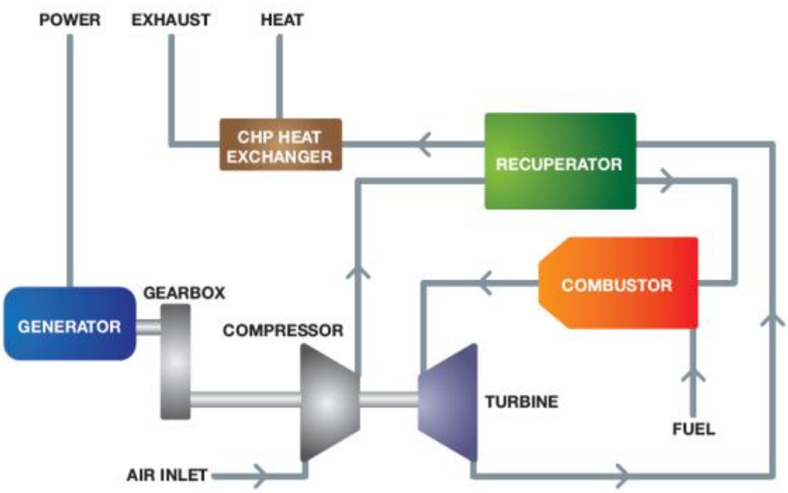

Figure 2. The scheme of a microturbine-based CHP system (Darrow et al. 2015).

The basis of the microturbine is the single-stage radial flow compressor and turbine. Unlike depicted in Figure 2, this turbocompressor is usually installed on the single shaft along with the generator. Microturbines, unlike large turbines, use single-stage radial flow compressors and turbines, because radial flow turbomachines operate at low volume air streams and combustion gases with higher efficiency than axial components. Single-shaft turbines are designed to operate at high speeds and to produce electricity as high-frequency alternating current (AC). The generator output is transformed to direct current (DC) and then converted to 50 or 60 Hz AC. (Darrow et al. 2015) For the European countries, Russia and Asia, 50 Hz is a standard, and for the United States - 60 Hz. (Goldstein 2003)

The shaft rotates with the speed up to 100 000 revolutions per minute (rpm) and it is supported on bearings. Air bearings or conventional lubricated bearings are usually used in the microturbine units. In the air bearings, a thin layer of pressurized air allows the turbine to spin with low friction and high rotating speed. One of the most well-established type of oil-lubricated bearings is the bearings with the ceramic surface. They have advantages in operational values, working temperature, and lubricant flow comparing to the other kinds of oil-lubricated bearings. However, ceramic surface bearings need additional equipment: oil pump, filtration, and cooling technologies. These components add more cost and maintenance to the system. (Darrow et al. 2015)

The recuperator is a heat exchanger. It is used for preheating of compressed air, which enters the combustor, by the hot exhaust gas. Due to this, the amount of fuel, required for the targeted turbine inlet temperature, is reduced and electric efficiency increased. In CHP use, an additional heat exchanger unit is integrated for the recuperation of remaining heat in the exhaust gas. Exhaust heat is suited for various applications, for instance, space heating, cooling, and dehumidifying systems. (Darrow et al. 2015)

Electrical power in microturbine turbomachinery can be produced by a high-speed generator, which turns on the single turbocompressor shaft or by a speed reduction gearbox, which drives a generator with the speed of 3 000 or 3 600 rpm. In the high-speed generator system, the single-shaft construction uses a constant magnet and an air-cooled generator, which produce high-frequency alternating voltage and current. A power conditioning unit rectifies this high frequency current to grid frequency, during this process an efficiency penalty is approximately 5 percent. Microturbines typically have controls, which allow the system to work in parallel or independent of the grid. (Darrow et al. 2015)

3.2 Microturbine Turbec T100

In this thesis, the micro-CHP unit with Turbec T100 Power and Heat (PH) microturbine, based on a regenerative Brayton cycle, is used. It is a modular unit, generating electricity and heat with high efficiency and low emission levels. This microturbine satisfies the requirements of the European basic health and safety policies and follows Machinery Directive 98/37/EC, Noise Directive 2000/14/EC, Electromagnetic Compatiblity Directive 2004/108/EC and Low Voltage Directive 2008/95/EC. (Turbec 2009)

3.2.1 Main components

The schematic representation of the flows in the power generating unit is illustrated in Figure 3. It provides a visual demonstration of the Turbec T100 operation. The ambient air flows around the generator and enters the compressor in axial direction. After compression, the air leaves the compressor radially. The blue color represents the air with high pressure. It flows through the recuperator where the flue gases preheat it. Pink color represents the preheated air with high pressure. In the combustor, it is mixed with the gaseous fuel and then burned. The red color represents the flue gases that enter the turbine in radial direction and leave axially. The flue gas preheats the compressed air in the recuperator and leave the unit. (Turbec 2009)

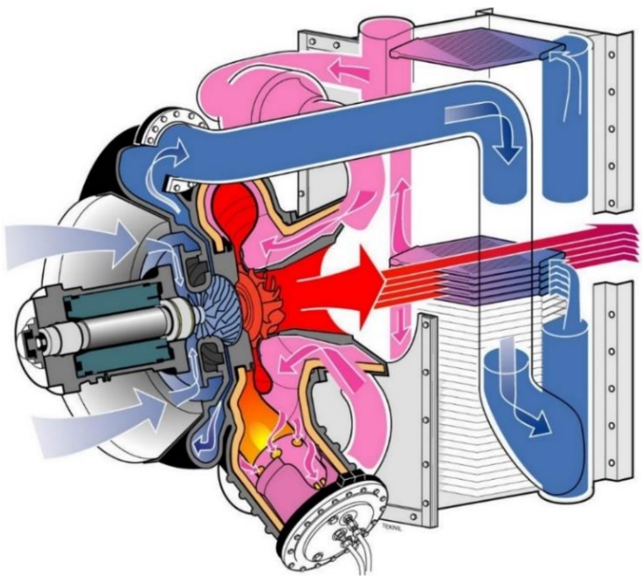

Figure 3. The schematic representation of Turbec T100 power module (Turbec 2009).

The power module is coupled with an exhaust gas heat exchanger. It is a gas-water counter-current flow heat exchanger, that is located right after the recuperator. The heat from the exhaust gasses is used for water heating in the exhaust gas heat exchanger. The amount of generated heat is directly related to the amount of generated electricity. Sometimes less heat is needed than available. In cases when too much heat is extended to the water, the water can become boiling, which is harmful to the heat exchanger. Thus, the amount of supplied heat must be controlled and this is done using a bypass system, in which exhaust gasses are diverted either totally or partially around the heat exchanger. The outlet water temperature differs according to the input water parameters, temperature, and mass flow. The exhaust gases exit from this gas heat exchanger through an exhaust pipe and chimney. (Turbec 2009)

The power module includes the following subsystems:

- Gas turbine engine.
- Electrical generator. The high-speed generator is water-cooled, and has high efficiency. It generates the electric power by a permanent magnet, supported with two bearings one on each side.
- Electrical system. The high-frequency AC power from the generator is transformed to the needed grid voltage and frequency. A transmission-line filter and a transformer normalizes the AC output.
- The microturbine is guided and governed by an automatic supervision and control system. Due to this, the turbine does not require attendance in person under normal operation. In case of any faulty operation or failure of the grid, the system automatically shuts down. (Turbec 2009)

The major elements of the gas turbine engine are as follows:

- Housing. In the microturbine unit, the generator and the rotating components are installed on the same shaft in the same housing.
- Compressor. A radial centrifugal compressor is used. It has the pressure ratio of 4,5.
- Recuperator. In the recuperator, heat is transferred from the hot exhaust gases to the compressed air entering the combustion chamber.

- Combustion chamber. In the start-up, an electrical igniter in the combustion chamber ignites the mixture of air and fuel. During operation, the combustion process is continuous.
- Turbine. Similarly to the compressor, the turbine is of the radial type. The gases enter the turbine at the temperature of 950 °C and pressure 4,5 bar and leave the turbine at atmospheric pressure and the temperature of 650 °C. (Turbec 2009)

Besides main components, there are several auxiliary systems, which are classified as the following subsystems:

- Lubrication system, is essential for lubricating the squeezed film bearings located on the rotor shaft.
- A separate closed cooling water system, needed for cooling the generator.
- Air intake and ventilation system. A microturbine unit placed indoors draws ambient air. In the unit, the flow of air is separated into 2 different flows. The main air flow is needed for combustion process, and the secondary flow - for ventilation in the power module.
- Fuel gas system includes a fuel control system and fuel booster. In case, the gas pressure is less than 6 bar (g), a fuel booster is used for the gas pressure increasing. The gaseous fuel enters the fuel booster and then discharged to the fuel control system.
- Buffer air system. The gas turbine compressor supplies this system with air. It is needed for preventing from the ingestion of the lubrication oil in the gas turbine and the electric generator. (Turbec 2009)

3.2.2 Performance

Figure 4 illustrates the influence of an air inlet temperature on the Turbec T100 electrical output and efficiency at full load when using low-pressure gas of 0,02 bar (g). Using high-pressure gas, the electrical output increase is approximately 5 kW and the electrical efficiency increase is 1,5 percent. (Turbec 2009)

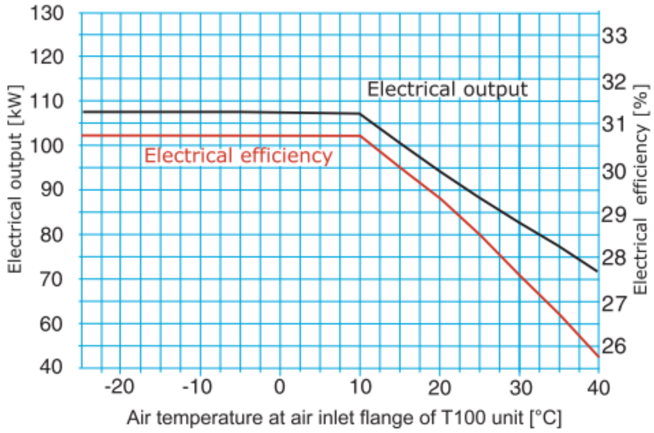

Figure 4. The influence of an air inlet temperature on the electrical output and efficiency (Turbec 2009).

Characteristic to gas turbines, the output and efficiency increase as air temperature decreases. Below 10 °C, the performance is maintained at constant level due to limited capacity of the generator and power electronics. (Turbec 2009)

Figure 5 contains 2 charts illustrating how air inlet temperature (left) and water inlet temperature (right) influence on T100 PH microturbine heat output and total efficiency based on low-pressure gas sources of 0,02 bar (g).

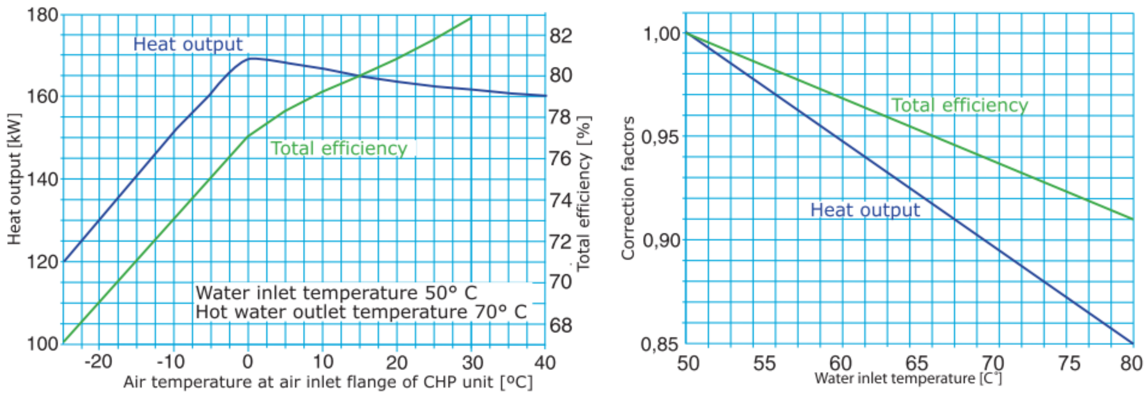

Figure 5. The influence of an air inlet temperature (left) and water inlet temperature (right) on heat output and total efficiency (Turbec 2009).

The correction factors in the right chart scale the performance value. In accordance with the factor for heat output for instance, when the inlet water temperature decreases by 10 °C then the thermal output will decrease by nearly 8 kW. (Turbec 2009)

Figure 6 contains 2 charts presenting the influence of inlet pressure drop (left) and outlet pressure drop (right) on the performance characteristics of the microturbine unit.

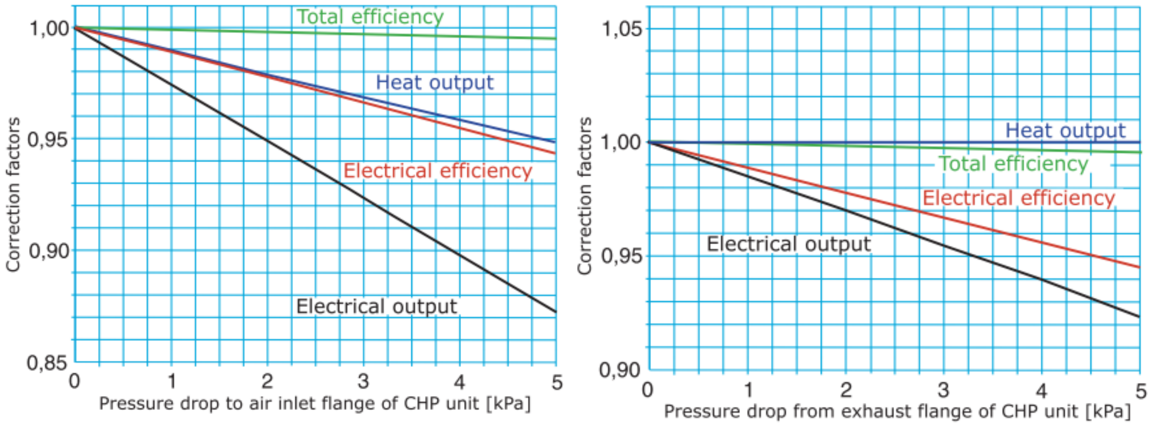

Figure 6. The influence of inlet pressure drop (left) and outlet pressure drop (right) on T100 performance (Turbec 2009).

Figure 7 contains 2 charts presenting the influence of part load on electrical and total efficiencies (left) and site elevation (right) on the performance characteristics of microturbine unit.

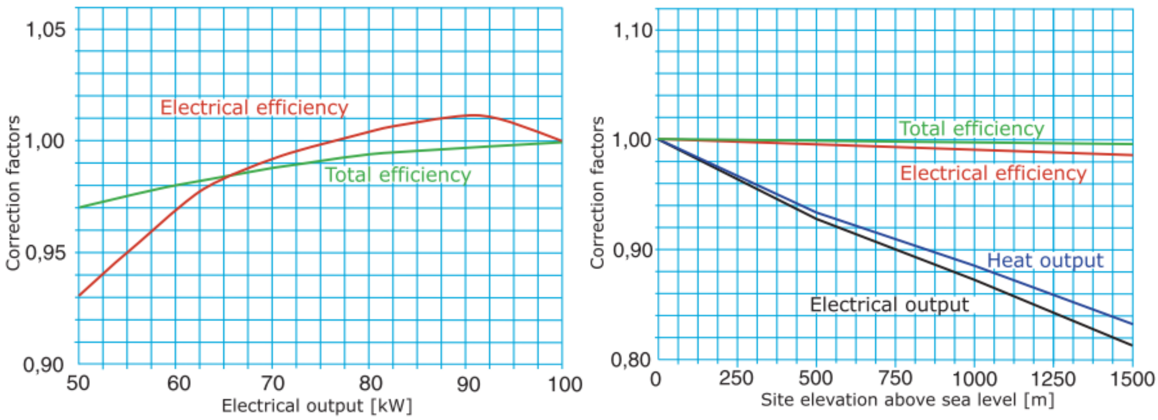

Figure 7. The influence of part load (left) and elevation (right) on performance (Turbec 2009).

In case when less than full load power is needed from a turbine, its output is decreased by decreasing the speed of rotation, which decreases the temperature rise and pressure ratio in the compressor and temperature drop in the turbine, and by decreasing turbine inlet temperature, so the recuperator inlet temperature does not increase. In addition to decreasing power output, this change in working conditions also affects the efficiencies. In the T100 microturbine, the efficiency reduction is minimized by using the speed of rotation as the primary power control method. (Turbec 2009)

The density of air depends on the site elevation above the sea level. The density of air reduces at increasing altitudes, and, as a result, the unit power and heat output reduces. (Turbec 2009)

3.2.3 Maintenance concept

The maintenance concept is based on the several principles:

- Remote monitoring and control system, used for distant control,
- Predeclared functions in case of corrective maintenance,
- A detailed preventive maintenance system,
- Support and maintenance service. (Turbec 2009)

The simple design of the microturbine contributes to the long-term reliability of operation. Failure diagnostics, monitoring of operation, and device status conditions are enabled by remote monitoring and control system. The module structure of the unit does not require special lifting equipment. The unit is designed with predeclared functions for corrective maintenance, such as filter changes, automatic warnings, and alerts for pertinent conditions. The design service life is approximately 60 000 hours with a scheduled overhaul after 30 000 hours of operation, and limited inspection and maintenance services in between. The maintenance agreement is based on the service partner coverage. Manufacturer provides the supply of spare parts, technical assistance, and instructions. The on-site assistance is provided by the local service partner. (Turbec 2009)

3.3 The economics of combined heat and power

3.3.1 Capital cost

In this paragraph, capital costs for the basic CHP units with microturbines as a prime mover are presented. It is considered that the waste heat from the exhaust gases is utilized for water heating. Installed costs may differ significantly, as they depend on the size of the installed equipment, geographic region, market situation, emissions control system, labor and whether the microturbine unit is new or updated. The typical unit (generator package) includes the microturbine and power electronics. (Darrow et al. 2015) Table 2 presents cost estimates for four micro-CHP systems with nominal capacity from 30 to 250 kW.

Table 2. Equipment and installation costs for typical microturbine based CHP units (Darrow et al. 2015).

	1	2	3	4
Electric capacity				
Nominal capacity [kW]	30	65	200	250
Net capacity [kW]	28	61	190	240
Equipment costs				
Generator package [$]	53 100	112 900	359 300	441 200
Heat recovery [$]	13 500	0	0	0
Fuel gas compression [$]	8 700	16 400	42 600	0
Total equipment [$]	75 300	129 300	401 900	411 200
Total equipment [$ kW^{-1}]	2 689	2 120	2 120	1 840
Installation costs				
Labor and materials [$]	22 600	28 400	80 400	83 800
Project and construction [$]	9 000	15 500	48 200	52 900
Turbine, w/o gas cleanup [$]	4 300	3 220	3 150	2 720
Gas cleanup [$ kW^{-1}]	2 590	1 930	1 250	1 150
Engineering and fees [$]	9 000	15 500	44 200	48 500
Project contingency [$]	3 800	6 500	20 100	22 100
Financing [$]	700	1 200	3 700	4 100
Total other costs [$]	45 100	67 100	196 600	211 400
Total other costs [$ kW^{-1}]	1 611	1 100	1 035	881
Total installed cost [$]	124 700	199 620	601 650	655 320
Total installed cost [$ kW^{-1}]	4 160	3 070	3 000	2 620

The table conforms to the general trend of decreasing specific costs as the unit size increases.

Some additional equipment is needed for these cogeneration systems. In the system with 30 kW nominal capacity, a heat recovery system, controllers, and remote monitoring system have been installed. Fuel gas compression equipment was installed in all units except for the 250 kW case. Labor and material costs include the labor cost for the civil, mechanical, and electrical work and materials. There are additional, or soft costs, which depend significantly on installation and project management. Engineering costs are needed to the system engineering and its further integration with the consumer’s electrical and mechanical systems. Project and construction costs include the general contractor profit margin and operation guarantees. Contingency is estimated to be approximately 5 percent of the total equipment cost for all systems. (Darrow et al. 2015)

3.3.2 Maintenance

Maintenance costs depend on the size of the microturbine, fuel type, and technology. Usually, the manufacturer offers maintenance contracts which cover scheduled and unscheduled situations. (Darrow et al. 2015) The maintenance costs for typical microturbine based CHP units are presented in Table 3.

Table 3. Maintenance costs for typical microturbine based CHP units (Darrow et al. 2015).

	1	2	3	4
Nominal electricity capacity [kW]	30	65	200	250
Fixed [$ kW^{-1} year]	-	-	-	9 120
Variable [$ kW^{-1}]	-	-	-	0,010
Average at 6 000 h/year operation [$ kW^{-1}]	-	0,013	0,016	0,011

Fuel and operational conditions have the direct influence on maintenance conditions. Units operating on waste gas and liquid fuel, usually need more frequent maintenance than natural gas applications. Units installed in dusty and dirty places need more frequent inspections and filter replacement. (Darrow et al. 2015)

4 BIOGAS USAGE

This chapter provides basic information about biogas from anaerobic digestion and landfill gas — what they are composed of, how they are produced, and the conditions that influence the generation.

Majority of the current energy demands are covered through the combustion of fossil fuels, such as natural gas, oil, and coal. However, the utilization of fossil fuels is expected to decrease in the coming decades, because of the new emissions policy, depletion of fossil fuel reserves and the necessity of sustainable energy systems. (Ghenai 2014) Traditionally microturbines have been designed for utilizing natural gas as a primary fuel. However, they can operate on a wide variety of fuels, including distillate oil, liquefied petroleum gas, sour gas, biogas, industrial waste gases and manufactured gases. (Goldstein 2003) In this thesis three kinds of fuels with different chemical composition are investigated: natural gas, biogas from anaerobic digestion and landfill gas. Natural gas is used as a traditional fuel for the microturbine and renewable fuels as the possible alternatives to conventional fuel. (Abbasi et al. 2012)

When any organic matter – such as food waste, plant residues, animal manure, sewage sludge, and biodegradable urban solid waste – decomposes with no free oxygen, it usually produces a gas which has from 40 to 70 percent of methane (CH_4), the rest part is predominantly carbon dioxide (CO_2) with traces of other gases. During combustion, the gas burns with no soot and offensive odor, similarly to liquefied petroleum gas and natural gas. This gas is generally called biogas. The term biogas is used exclusively to define the combustible CH_4-CO_2 mixture (traces of other gases as well) that is produced by the anaerobic decomposition of organic materials. A mixture of methane and carbon dioxide components is not the only possible gas by anaerobic degradation of organic materials. Of the two, methane can be achieved only if there are methane-producing bacteria in the anaerobic decomposition process. Under a different set of conditions, and with other types of anaerobic micro-organisms, gases like hydrogen or hydrogen sulphide may be produced. But methanogenic bacteria are widespread in nature and generally anaerobic digestion results in the production of the mostly CH_4–CO_2 mixture which is considered as biogas. (Abbasi et al. 2012)

Landfill gas is a natural byproduct of decomposition process of organic matters in municipal solid, commercial, and industrial wastes. There are a lot of landfills in the world and particularly in Europe to collect and utilize landfill gas for power and heat production. When landfill gas escapes to the atmosphere, it contains methane and is a potent greenhouse gas. Therefore, prevention of gas leak to atmosphere and its usage as a renewable fuel source is a winning situation from the environmental viewpoint. (Abbasi et al. 2012)

Same type of biogas can also be generated from forest or wood biomass in a thermal gasification process. Although the product is similar (methane from renewable sources), it is often considered as synthetic natural gas, and has also great potential. (Abbasi et al. 2012)

4.1 Advantages of biogas technologies

The generation and usage of biogas from anaerobic digestion and landfill gas ensures environmental and socio-economic benefits for the country as well as for the farmers which take part in it. Local biogas production increases local economic opportunities, provides new workplaces in rural regions and stimulates purchasing power. It is beneficial to living standards and promotes economic and social development. (Seadi et al. 2008)

Biogas utilization has the following benefits for the society:

- greenhouse gas emissions reduction and global warming mitigation,
- increase of independence on imported fossil fuels,
- promotion of European Union energy and environmental goals,
- waste reduction,
- job creation,
- flexible and efficient end usage of biogas,
- low water needs. (Seadi et al. 2008)

These benefits are discussed in more detail below. The global energy generation depends on fossil fuels such as crude oil, lignite, hard coal, and natural gas. During the millions of years, remains of plants and animals have been slowly decomposed and formed fossil fuels in the lithosphere. That is why fossil fuels are nonrenewable resources and their amount deplets faster than new ones come into being. (Seadi et al. 2008)

The World's economy depends a lot on crude oil. There are discussions among scientists on how long crude oil will be available, and according to recent publications, the "peak oil production" has already been passed. (Seadi et al. 2008) Figure 8 illustrates the scenario of World oil production and "peak oil" among different regions and decades.

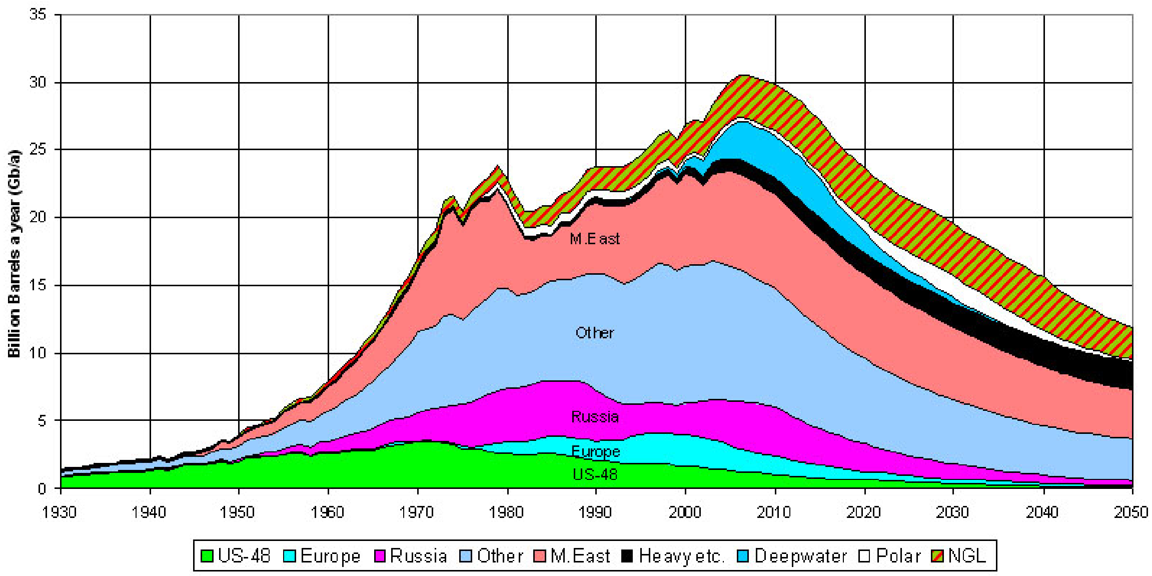

Figure 8. The scenario of World oil production and "peak oil" (Seadi et al. 2008).

As opposed to fossil fuels, biogas from anaerobic digestion and landfill gas are renewable, as they are generated from biomass and waste. Biogases can not only enhance the energy balance of a region but also make a vital contribution to the conservation of the natural resources and to nature protection. (Seadi et al. 2008)

The next benefit is greenhouse gas emissions reduction and global warming mitigation. Usage of fossil fuels converts carbon, which has been kept in the lithosphere and delivers it as CO_2 into the atmosphere. An increase of the current carbon dioxide concentration is the major reason of climate change because CO_2 is a greenhouse gas. During biogas utilization, carbon dioxide also releases. Comparing to fossil fuels, carbon in biogas was lately taken up from the atmosphere by the photosynthetic process of the plants. Thus, the biogas carbon cycle is closed in a short period of time. Due to biogas generation, the concentration of methane and nitrous oxides in the atmosphere is also reduced. In the future, when biogas replaces fossil fuels, a decrease of emissions of carbon dioxide, methane, and nitrous oxides into the atmosphere will take place, and it will contribute mitigation of global warming. (Seadi et al. 2008)

Biogas utilization increases independence on imported fossil fuels. Fossil fuels are limited sources, located in several geographical regions of the planet. For the countries with a lack of fossil fuels, this creates a constant and insecure position of dependence on energy imports. For example, most of the countries in Europe are strongly dependent on energy and fossil fuels import. For wide development and implementation of renewable energy systems, including biogas from anaerobic digestion and landfill gas, national and regional biomass sources and wastes are considered as basic resources, and they will guarantee the security of energy supply and improve local independence on energy import. (Seadi et al. 2008)

The next benefit is the promotion of European Union energy and environmental goals. Prevention of climate change is one of the main targets of the European energy and environmental policies. The European aims of increasing renewable energy generation, reducing GHG emissions and applying smart waste treatment are based on the agreement of the European Union member states to promote correct activities to reach them. The generation and usage of biogas is essential in order to ensure the realization of all three targets at the same time. (Seadi et al. 2008)

Waste reduction is an important aspect of the modern society. One of the prime benefits of biogas generation is its capability to convert waste into a useful resource, by using it as a substrate for anaerobic processes. Many countries in the world have problems connected with the excess production of organic waste. Biogas generation is a good solution for compliance with more and more restrictive European waste management regulations. Biogas production also helps to reduce the waste amount and costs for waste disposal. (Seadi et al. 2008)

The last but not least benefits of biogas for the society are job creation, flexible and efficient end usage of biogas and low water needs. Generation of biogas needs labor force for maintaining all the functions of the biogas plants. It means that the growth of a national biogas sector helps to establish new plants, increases the quality of life in rural areas and creates new workplaces. Biogas is a flexible energy material, it can be utilized in various applications. Biogas can be easily used for cooking and lighting, but in the present time biogas is utilized commonly in CHP units, as fuel for vehicles or fuel cells or it is upgraded and fed into natural gas grids. Even comparing to other biofuels, biogas has several benefits. One of them is that the biogas production requires less volume of process water. This is an essential characteristic related to the prospective future water shortages in the planet. (Seadi et al. 2008)

In addition to all advantages listed above, biogas can bring the following benefits to involved farmers:

- carbon credits for reduction of methane emissions or renewable energy tariffs,
- additional income from electricity and heat generation when fed into the grid,
- digestate can be used as a soil fertilizer,
- closed nutrient cycle,
- possibility to use various feedstock,
- reduced odors and flies,
- veterinary safety. (Seadi et al. 2008)

One of the most valuable benefits for farmers is a possibility to have an additional income and special renewable energy tariffs. Production and utilization of biogas on plants makes these technologies economically feasible for farmers and ensures them additional income. The farmers become also energy suppliers and waste treatment operators. (Seadi et al. 2008)

Digestate is a perfect soil fertilizer, which can be used in farms. Biogas plants are not only a provider of energy but also a digested substrate. It is rich in nitrogen, phosphorus, potassium, and micronutrients. Digestate can be used on soils with the technics for using liquid manure. When comparing to raw animal manure, digestate has higher fertilizer efficiency due to higher homogeneity and nutrient existence, also lower carbon-to-nitrogen ratio, and noticeably reduced odors. Low carbon-to-nitrogen ratio means that digestate has a better short term N-fertilization value. (Seadi et al. 2008)

The third benefit for the farmers is the closed nutrient and carbon cycle. Methane is utilized for energy generation and the carbon dioxide is released to the atmosphere and re-uptaken by plants during photosynthesis process. Biogas generation can be successfully integrated into common and organic farming, where it is possible to use digestate to replace chemical fertilizers, which were generated with consumption of large volumes of fossil power. (Seadi et al. 2008)

The next benefit of biogas for farmers is the flexibility to use various feedstock. A wide range of feedstock, agricultural and wastes, suitable for the biogas generation is shown in Table 4. One major benefit of biogas generation is the possibility to utilize wet biomass as feedstock, it has a moisture content higher than 60 – 70 percent. A lot of different energy crops such as grains, maize, and rapeseed, has been utilized as feedstock for generation of biogas in Germany and Austria. As well as energy crops, all types of agricultural residues, which cannot be used as food or results from unfavorable growing and weather conditions, can be utilized to generate biogas and fertilizer. Animal by-products, which are not good for human usage, can also be utilized for biogas production. (Seadi et al. 2008)

Table 4. Biogas feedstocks (European Biogas Association 2009).

Agriculture	Waste streams
Manure	Landfill
Energy crops, catch crops	Sewage sludge
Landscape management	Municipal solid waste
Grass	Food waste
Other by-products	Other waste

Reduction of odors and flies is also a major benefit. Storage and usage of animal liquid manure and municipal solid waste are responsible for strong, unpleasant odors and attract flies. Anaerobic digestion and landfill gas production reduce unpleasant odors by up to 80 percent. Digestate has almost no odor and remaining ammonia odors vanish into space quickly after application digestate as fertilizer. (Seadi et al. 2008)

Veterinary safety is also important. It has been proven, that the application of digestate as fertilizer, compared to untreated manure and slurries, can be beneficial for maintaining veterinary safety. To be suitable for utilization as fertilizer, digestate has to go through a special sanitation process. The goal of sanitation process is to deactivate pathogens and weed seeds and to avert diseases transmission. (Seadi et al. 2008)

4.2 Process engineering

4.2.1 Biogas from anaerobic digestion

The process of biogas generation is called anaerobic digestion. Anaerobic degradation process is the biological oxidation process of organic materials with the special micro-organisms without of free oxygen. During the fermentation, complex biodegradable organics break down into four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (acetotrophic or hydrogenotrophic). (Abbasi et al. 2012) The process is shown in Figure 9.

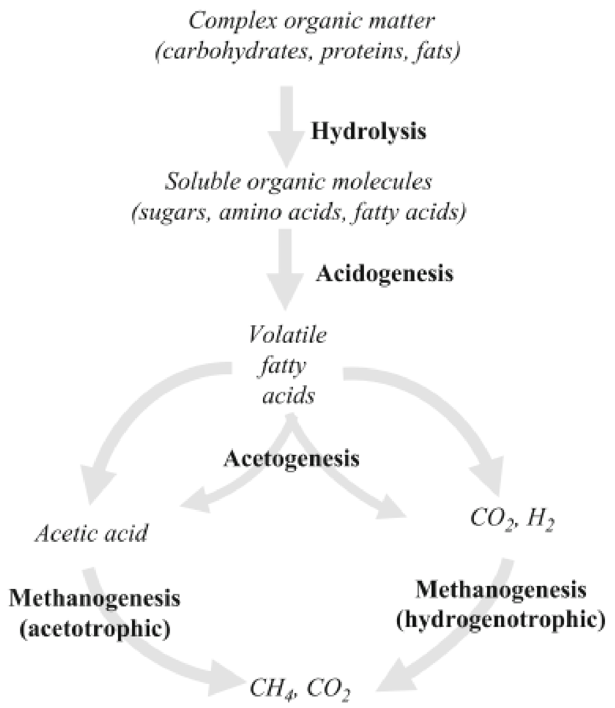

Figure 9. The steps of the anaerobic digestion process (Abbasi et al. 2012).

Basically, hydrolysis is the first step in the chemical process. The complex organic materials – polymers – biodegrade into smaller elements, such as mono- and oligomers. Polymers such as carbohydrates, lipids, nucleic acids, and proteins are transformed into glucose, glycerol, purines, and pyridines. Hydrolytic micro-organisms produce hydrolytic enzymes, by transforming biopolymers into simpler and soluble elements. Micro-organisms involved in the process, then decompose the hydrolysis end-products and use these products for maintaining their own metabolic needs. (Abbasi et al. 2012)

During acidogenesis process, the end-products from hydrolysis stage are transformed by special fermentative bacteria (acidogenic) into methanogenic elements. Monosaccharides, amino acids, and fatty acids are decomposed into acetate, carbon dioxide and hydrogen (70 percent) and, also into volatile fatty acids and alcohols (30 percent). (Abbasi et al. 2012)

Volatile fatty acids and alcohols are oxidized to methanogenic elements such as acetate, hydrogen and carbon dioxide. Hydrogen generation leads to the hydrogen partial pressure increase. This can be considered as a waste product of the process and retards the metabolism of the acetogenic bacteria. During methanogenesis, hydrogen is transformed into methane. Acetogenesis and methanogenesis generally occur at the same time, as a symbiosis of two groups of micro-organisms. (Abbasi et al. 2012)

The methane and carbon dioxide generation from an intermediary product is achieved with methanogenic bacteria. From acetate is generally produced about 70 percent of all methane, and rest 30 percent is generated from hydrogen and carbon dioxide conversion. Methanogenesis is an important stage in the whole anaerobic digestion process, because of its slow biochemical reaction. Working conditions, such as raw material composition, feeding rate, temperature, and pH (potential of hydrogen), have a strong influence on the process of methanogenesis. Digester overwork, temperature changes or large penetration of oxygen can be a reason of a breakdown of methane generation. (Seadi et al. 2008)

4.2.2 Landfill gas

Landfill gas composition includes a mixture of hundreds of various gases. By volume, it is typically composed of 35 to 65 percent methane and 15 to 40 percent carbon dioxide with a small amount of different gases. Landfill gas is produced in three steps listed below:

- bacterial decomposition,
- volatilization,
- chemical reactions — formation of landfill gas. (Agency for Toxic Substances and Disease Registry 2001)

The first process of landfill gas formation is the bacterial decomposition. The majority of landfill gas is formed by bacterial decomposition. It takes place when organic waste is decomposed by bacteria, which are naturally existing in the wastes and in the soil needed for covering the landfill. Solid wastes include organic fractions of food, yard waste, street refuse, textiles, as well as woody and paper materials. Bacteria brakes down organic wastes in four stages, and the composition of the gas produced changes with each stage of decomposition. The first is aerobic and last three are anaerobic. (Agency for Toxic Substances and Disease Registry 2001)

The second phase of landfill gas production is volatilization. Landfill gas can be produced when waste, especially organic matters, transform from a liquid or a solid form into a vapor. This process is called volatilization. Non-methane organic compounds in landfill gas are the consequence of volatilization of some chemical elements disposed of in the landfill. (Agency for Toxic Substances and Disease Registry 2001)

The final stage of landfill gas production are chemical reactions. Landfill gas, with non-methane organic compounds, can be produced by the chemical reactions of special chemical elements existing in waste. When chlorine bleach and ammonia react with each other, dangerous gases are created. (Agency for Toxic Substances and Disease Registry 2001)

The rate and amount of landfill gas created depends on the properties of the waste, such as composition and age of waste, and on several environmental conditions, such as the oxygen volume in the landfill, moisture content, and temperature:

- Waste composition. The more organic materials are in a landfill, the more landfill gas is created by the bacteria. The more chemical elements brake down in the landfill, the more likely non-methane organic compounds and other gases will be created either in volatilization phase or chemical reactions.
- Age of waste. Usually, if refuse is buried a short time ago, less than 10 years, it creates more landfill gas than the older refuse. Commonly, maximum level of gas generation is from 5 to 7 years after the refuse is buried.
- Oxygen volume in the landfill. Methane can be created only in the absence of oxygen in the landfill.

- Moisture content. The existence of moisture in a waste boosts gas generation because it contributes bacterial decomposition. Moisture can also encourage chemical reactions that create gases.
- Temperature. As the temperature in the landfill increases, the rate of bacterial decomposition increases, the result of this is the increase in gas production. Raised temperature can also raise rates of volatilization process and chemical reactions. (Agency for Toxic Substances and Disease Registry 2001)

4.3 Fuel characteristics

Biogas is basically a mixture of methane and carbon dioxide. Biogas is generated essentially at or slightly below the atmospheric pressure, so before utilizing, it must be compressed. After being compressed, biogas must be cooled and scrubbed or filtrated. It is required to remove compressor oil, condensate, and any particulate matters which can be entrained in the original gas. Extra requirements for raw biogas treatment are the main reason of higher costs of biogas-powered plants compared to natural gas. Several factors, such as process design, type of the substrate used for the digestion, temperature, and retention period, influence on biogas composition and the chemical properties. The energy content of biogas is limited in methane. (Darrow et al. 2015)

Natural gas is one of the most widely used fuels for energy generation. When combusted, it is a cleaner-burning fuel compared to oil or diesel. However, natural gas also includes active elements, like sulfur, and inert elements, like nitrogen and carbon dioxide. It has rather high octane number from 110 to 130, and it can be utilized in high-compression engines. It can be stored as a compressed fuel, so-called compressed natural gas, or at low temperatures approximately minus 162 °C in liquid form as liquefied natural gas. Utilization of natural gas gives less carbon dioxide emissions in comparison with the utilization of diesel and gasoline. (Demirbas 2010)

Natural gas forms deep below the ground, generally in places near coal and oil. Mostly it consists of methane. However, it includes other chemical compounds, such as ethane and propane. In case when mixture consists only of these compounds, it is identified as dry natural gas, because there will be no fluid components at standard conditions. Natural gas can also include nonhydrocarbon elements, for example, water vapor, carbon dioxide, and hydrogen sulfide. (Demirbas 2010)

Table 5 presents the properties and chemical composition of biogas from anaerobic digestion, landfill gas and natural gas in the Danish transmission grid and minimum/maximum values for each gas component. The list variation of each parameter is based on typical data and thus does not cover extreme maximum or minimum values.

Table 5. Fuel properties and composition. Landfill gas and biogas data from (Swedish Gas Technology Centre 2012), natural gas data from (Energinet 2013).

Quantity	Landfill gas	Biogas from AD	Natural gas
Lower heating value [MJ kg^{-1}]	23 719	32 528	49 304
Density [kg Nm^{-3}]	1,3	1,1	0,818
Relative density [-]	1,1	0,9	0,633
Wobbe index [MJ Nm^{-3}]	18	27	54,96
Methane number [-]	> 130	> 135	73
Methane [% vol.]	45 (35 – 65)	65 (60 – 70)	89,64 (86,6 – 98,2)
Carbon dioxide [% vol.]	40 (15 – 40)	35 (30 – 40)	0,72 (0,03 – 2,50)
Hydrogen [% vol.]	0 – 3	-	-
Nitrogen [% vol.]	15 (5 – 40)	0,2	0,29 (0,25 – 5,25)
Oxygen [% vol.]	1 (0 – 5)	-	-
Ethane [% vol.]	-	-	5,87 (0,68 – 8,35)
Propane [% vol.]	-	-	2,32 (0,21 – 3,55)
I-butane [% vol.]	-	-	0,38 (0,03 – 0,48)
N-butane [% vol.]	-	-	0,53 (0,03 – 0,67)
I-pentane [% vol.]	-	-	0,12 (0,00 – 0,20)
N-pentane [% vol.]	-	-	0,078 (0,00 – 0,12)
Hexane+ [% vol.]	-	-	0,056 (0,00 – 0,11)

The chemical composition and properties of pipeline natural gas depend on the source and the processing method of the gas. Usually, it consists of over 90 percent methane and low amounts of ethane and other compounds. Natural gas at ambient temperature and pressure is a gaseous fuel. It has a very low energy density in comparison with other fossil fuels. (Demirbas 2010)

4.4 Support schemes for biogas in the EU

The production costs of biogas electricity basically are higher than that of traditional technologies. It is evident that costs differ significantly depending on the region and local conditions of the market, which will affect a lot the competitiveness compared to traditional power generation technologies. Biogas can be competitive with nuclear, gas, oil, or coal in case of regional conditions are in its favor. (Canton et al. 2010)

Set up in 2005, the EU Emission Trading System, covering power production from fossil fuels, presents a special cost for power-producing companies. Due to these costs, the competitiveness of biogas electricity is improved. Air pollution along with other ecological regulations similarly increase the generation costs of traditional power. In spite of all these exertions to internalize external costs, biogas power is more expensive than power generated by conventional technologies. Thus, different types of economic support schemes are used in the EU countries to promote the market integration of biogas power technologies. The goal is to create economies of scale and permit for continuous biogas technology development, which will cut the expenses and make these technologies competitive in the future. Another policy target is improving the security of supply by continuous diversification of the fuel types. The main biogas electricity support schemes consist of feed-in tariffs, feed-in premiums, and green certificates. (Canton et al. 2010)

Feed-in tariffs guarantee to the renewable power producers a special price for the power delivered into the grid. The discount and technology-specific tariffs are established by the government and are usually set for a time range from 10 to 20 years. The producers of renewable power are also facing a rather stable demand for their generated power because when power is fed into the grid, the system operator ensures the further distribution of the renewable power. Thus, the feed-in tariffs are a good mechanism for reducing the price and market risks, and they guarantee profitable business for the investors. Feed-in tariffs for electricity from biogas are used in Austria, Bosnia and Herzegovina, Bulgaria, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Luxembourg, Moldova, Montenegro, Portugal, Serbia, Slovakia, Switzerland, Turkey, Ukraine, and United Kingdom. (Canton et al. 2010)

A feed-in premium mechanism ensures the producers with a secure premium besides the electricity market price. The premiums are established by the government and the producers have profit from a guaranteed demand. Nevertheless, in these circumstances, the behavior of the electricity market price affects the price of biogas power. Feed-in premium for electricity from biogas are used in Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Italy, Lithuania, and Netherlands. (Canton et al. 2010)

Green certificates mechanism is generally based on a quota obligations. Consequently, the governments lay an obligation on consumers or suppliers to produce a certain amount of the electricity from renewables. Green certificates are given by the authorities to producers according to their amount of power generated from renewable sources. The quota obligations on electricity producers guarantee a demand for these certificates because producers will have to purchase certificates to fulfill the quotas. The main benefit of this mechanism is that it maintains competition between renewable suppliers as the certificate price depends on the demand and supply of green certificates. Green certificates for electricity from biogas are used in Belgium, Norway, Poland, Romania, Sweden, and United Kingdom. (Canton et al. 2010)

There are also support schemes for biogas heating, they include subsidies, loans, quotas system and tax regulations. Each mechanism is focused on promoting and supporting the growth of biogas use for heating purposes. (Canton et al. 2010)

5 MODEL DEVELOPMENT

5.1 IPSEpro software

IPSEpro is a software package for modeling and simulation of various types of process models for different applications and for using these models throughout the lifetime of process plants. It can be used in power plant engineering, chemical engineering, and other related fields. It includes a wide range of software modules for making calculations of heat balances, simulating the design and off-design performance parameters, planning and optimizing the upgrade of the plants on-line. IPSEpro was developed by Austrian company SimTech Simulation Technology. In this work, IPSEpro 6.0 has been used. (IPSEpro 2014)

IPSEpro can cover total service life of a system from draft design to plant operation. The key feature of IPSEpro software is its high flexibility, namely the possibility not only to use the standard component models and model libraries but also transform these model libraries to specific requirements as well. This software gives its users flexibility in choosing the operational characteristics of every component. Every model in IPSEpro is mathematically described by a number of equations and variables. Building a mathematical model of a process implies the joining all equations of the component models into a set of simultaneous equations. The component model creating process is simple and interactive. (IPSEpro 2014)

In IPSEpro software the operating values can be predicted at design and outside design (at off-design) conditions. The design model is composed of conservation equations, namely mass and heat, or energy, and closure equations, including fluid properties, process equations, heat transfer and friction. In other words, the design model is used for setting the universal model base to simulate steady-state characteristics with design operating values. The off-design model has additional correlations that affect some parameters in the model, such as mass flows, efficiencies, heat transfer coefficients, and pressure losses, and, consequently, together with the model base, determine the performance outside design conditions. (IPSEpro 2014)

The major modules of this package are the Process Simulation Environment (PSE) and the Model Development Kit (MDK). The user creates a component model mathematically and graphically with MDK. PSE project window is needed to choose the component icons from a library, place and create links between the components. This program enables effective data management and uses stable algorithms to make calculations fast. (IPSEpro 2014)

Model Development Kit is used to build up new component models or modify already existing models in a library. Users can create various model libraries with MDK to satisfy their requirements. A specific programming language is used in MDK for writing mathematical equations. To ease development process of the models, there is the icon editor. (IPSEpro 2014)

Process Simulation Environment in needed to build a process model based on components from a library and run the simulation. PSE has an easy to use flowsheet editor, where users can create process models by choosing the components from a menu list. Users can locate the components in the project window, establish the data in an interactive way, and link the components in accordance with their requirements. Process Simulation Environment uses effective mathematical methods that provide fast and exact calculations. After the simulation, all data associated with the streams in the process model is displayed immediately in the flowsheet and component-specific data can be retrieved by the user. The results of calculations can be shown in separate data tables, too. PSE automatically forms output results protocol for each calculation. (IPSEpro 2014)

One of the standard libraries in IPSEpro is the Advanced Power Plant Library, it was created for modeling a wide spectrum of thermal processes. This library enables its users to build and simulate steam power plants, gas turbines and combined cycle plants. The library includes models for design and off-design modes. The component models are developed in such way, that allows using all of them virtually together with a wide spectrum of applications. As an example, there is no need to distinguish between a compressor for gas or steam. The compressor model can use properly the operating fluids of the connected streams. (IPSEpro 2014)

PSXLink is an IPSEpro module allowing to integrate data between Process Simulation Environment and Microsoft Excel. This module was designed to transfer data obtained in the PSE to Microsoft Excel and due to this further analysis of the data, the creation of diagrams and reports are possible. Another benefit of the PSXLink is the possibility to transfer to MS-Excel series of various calculations with models. There is an option, to control PSE simulations directly from Microsoft Excel, so there is no need for additional screens. (IPSEpro 2014)

5.2 Microturbine model

The microturbine model has been constructed by Docent, D.Sc. (Tech.) Juha Kaikko at Lappeenranta University of Technology. The model uses microturbine Turbec T100 as a basis. At design point operation, only standard components are used. Outside design conditions, the operation of the compressor and turbine is determined using component-specific maps, while standard library models are applied for other components.

5.2.1 General assumptions and performance parameters

The model of the microturbine has several assumptions. Steady-state conditions prevail, so mass accumulation or heat capacity effects are not taken into account. Consequently, at any specific time, the mass flow of exhaust gas exiting the combustor and entering the turbine equals the sum of mass flows of air to the compressor and the fuel entering the combustion chamber. The combustion process is complete so that all carbon is converted to CO_2, all hydrogen to H_2O and all sulphur to SO_2. Nitrogen is also considered inert, thus it is impossible to calculate polluting emissions.

During the operation of the microturbine there are heat and pressure losses, and electric losses. Pressure losses are taken into account in the model to be as close as possible to the real values, but heat losses are not included in the model. Some of the produced electricity in the generator is needed for operation of the auxiliary systems in the power module, namely lubrication system, cooling system, air intake and ventilation system, fuel gas system including fuel booster, and buffer air system. The fuel gas compressor is included in the model but the electric power need for other auxiliary systems is considered in the generator efficiency. The generator efficiency is selected in such way so net electric power output of the unit is 100 kW with natural gas as a fuel and at standard ISO ambient conditions. The input values of the model do not comply with the ISO standard conditions completely, since there are pressure losses at the inlet and outlet.

The chemical composition of the natural gas used in simulation differs slightly from the original one presented in Table 6. There are five chemical components, namely I-butane, N-butane, I-pentane, N-pentane and Hexane+, which are not included in the IPSEpro simulations, due to absence of these components in the software list of chemical elements of the fuel. These components together represent approximately 1,6 percent of the total natural gas composition and they are included in propane value.

The recuperation ratio of counter-flow heat exchanger recuperator for preheating compressed air is assumed to be 0,850 at design conditions. Equation 1 is used to present the recuperation ratio of the recuperator:

$$\varepsilon = \frac{T_{\mathrm{air\_out}} - T_{\mathrm{air\_in}}}{T_{\mathrm{exh\_in}} - T_{\mathrm{air\_in}}} \tag{1}$$

ε	recuperation ratio	[-]
$T_{\mathrm{air\_out}}$	air outlet temperature of the recuperator	[K]
$T_{\mathrm{air\_in}}$	air inlet temperature of the recuperator	[K]
$T_{\mathrm{exh\_in}}$	exhaust gas inlet temperature of the recuperator	[K]

Performance parameters of the microturbine model are calculated by the IPSEpro software, taking into consideration all the simplifications listed above. These parameters can be described with the following five equations. Equation 2 presents the net electric power output:

$$P_{\mathrm{e}} = P_{\mathrm{g}} - P_{\mathrm{m}} \tag{2}$$

P_{e}	net electric power output	[kW]
P_{g}	generator power	[kW]
P_{m}	fuel gas compressor motor power	[kW]

Hot water for district heating is produced in the exhaust gas heat exchanger, which is a gas-water counter-current flow heat exchanger. The district heating output is determined by equation 3:

$$\Phi_{dh} = \dot{m}_{exh}\,(h_{exh\_in} - h_{exh\_out}) \quad (3)$$

Φ_{dh}	district heating output	[kW]
$\dot{m}_{exh}$	exhaust gas mass flow rate	[kg s^{-1}]
h_{exh_in}	exhaust gas inlet enthalpy	[kJ kg^{-1}]
h_{exh_out}	exhaust gas outlet enthalpy	[kJ kg^{-1}]

Gaseous fuel is used for the microturbine, in this thesis three kinds of fuels with different chemical composition are investigated. Equation 4 presents the fuel power:

$$\Phi_{f} = \dot{m}_{f}\,(h_{f} + LHV) \quad (4)$$

Φ_{f}	fuel input	[kW]
$\dot{m}_{f}$	fuel mass flow rate	[kg s^{-1}]
h_{f}	fuel enthalpy after compression	[kJ kg^{-1}]
LHV	lower heating value	[kJ kg^{-1}]

The electric efficiency of the system is defined as useful electric power output divided by the fuel input. The net electrical efficiency [-] can be evaluated by equation 5:

$$\eta_{e} = \frac{P_{e}}{\Phi_{f}} \quad (5)$$

The total efficiency of the system [-] includes the useful electric and district heating output and is determined by equation 6:

$$\eta_{tot} = \frac{P_{e}+\Phi_{dh}}{\Phi_{f}} \quad (6)$$

5.2.2 Compressor and turbine maps

The compressor and turbine were modeled using manufacturer maps that describe the interdependence between the operating parameters. Figure 10 illustrates the compressor performance considering isentropic efficiency (black continuous lines) and corrected speed (green dash lines) depending on the corrected mass flow (x-axis) and compression ratio (y-axis). (Caresana et al. 2014)

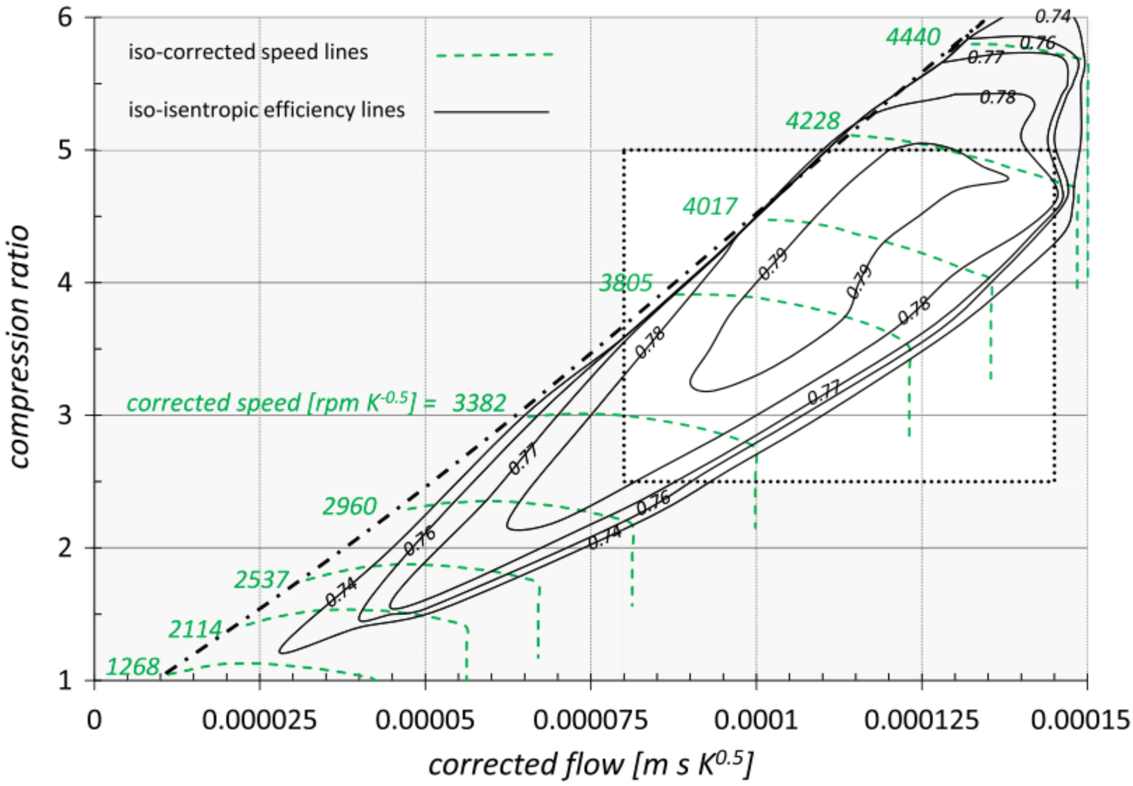

Figure 10. Compressor map (Caresana et al. 2014).

The map above corresponds to the following three equations. Equation 7 represents the corrected speed of the compressor:

$$\phi_{\mathrm{c}} = \frac{N}{\sqrt{T_{\mathrm{c\_in}}}} \tag{7}$$

ϕ_{c}	compressor corrected speed	[rpm K$^{-0,5}$]
N	compressor rotational speed	[rpm]
$T_{\mathrm{c\_in}}$	compressor inlet temperature	[K]

The compressor corrected mass flow is determined in accordance with equation 8:

$$\chi_{\mathrm{c}} = \frac{\dot{m}_{\mathrm{c}}}{p_{\mathrm{c\_in}}}\sqrt{T_{\mathrm{c\_in}}} \quad (8)$$

χ_{c}	compressor corrected mass flow	[m s K$^{-0,5}$]
$\dot{m}_{\mathrm{c}}$	compressor mass flow rate	[kg s^{-1}]
$p_{\mathrm{c\_in}}$	compressor inlet pressure	[Pa]

The pressure ratio (compression ratio) is calculated with equation 9:

$$\pi_{\mathrm{c}} = \frac{p_{\mathrm{c\_out}}}{p_{\mathrm{c\_in}}} \quad (9)$$

π_{c}	pressure ratio	[-]
$p_{\mathrm{c\_out}}$	compressor outlet pressure	[Pa]

Knowing two of these three values, the third value and the compressor isentropic efficiency can be determined from the compressor map. (Caresana et al. 2014)

Figure 11 illustrates the turbine behavior considering the isentropic efficiency (black continuous lines) and the corrected speed (green dash lines) depending on the corrected mass flow (x-axis) and expansion ratio (y-axis). (Caresana et al. 2014)

Similarly to the compressor map, turbine map is described with several equations, listed below. The corrected speed may be found with equation 10:

$$\phi_t = \frac{N}{\sqrt{TIT}} \quad (10)$$

ϕ_t	turbine corrected speed	[rpm K$^{-0,5}$]
N	turbine rotational speed	[rpm]
TIT	turbine inlet temperature	[K]

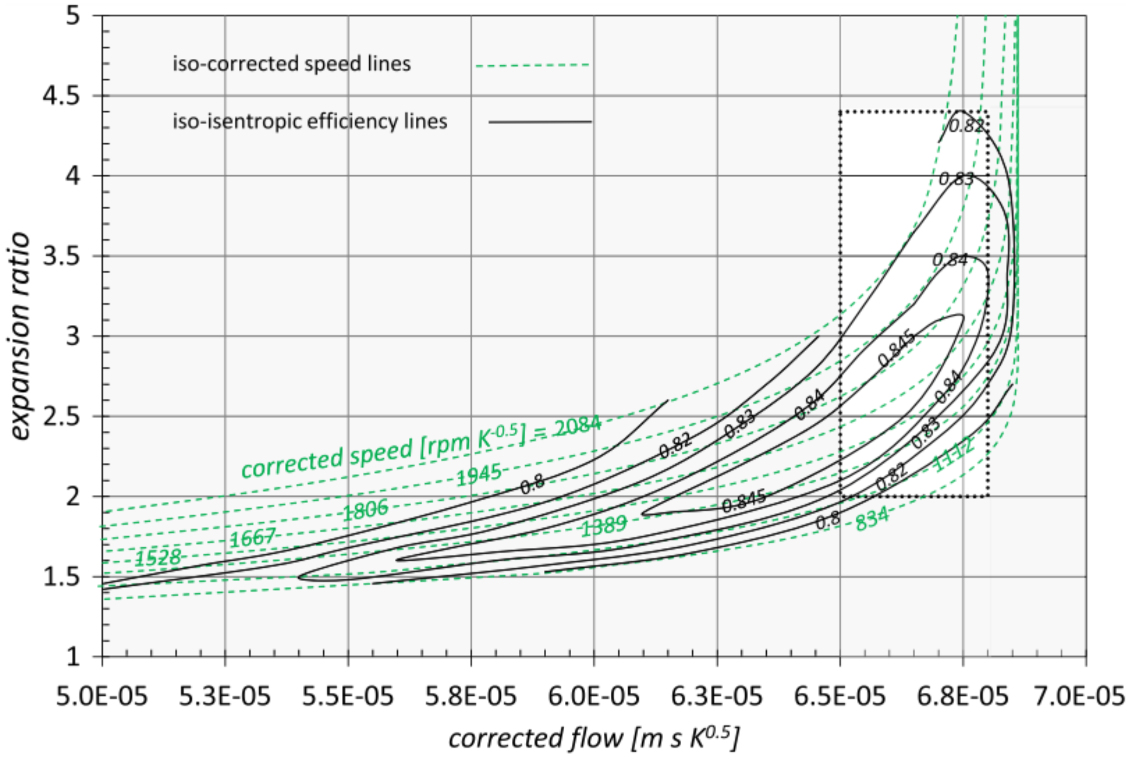

Figure 11. Turbine map (Caresana et al. 2014).

The turbine corrected mass flow can be described with equation 11:

$$\chi_t = \frac{\dot{m}_{exh}}{p_{t\_in}} \sqrt{TIT} \tag{11}$$

χ_t	turbine corrected mass flow	[m s K$^{-0,5}$]
$\dot{m}_{exh}$	exhaust gas mass flow rate	[kg s^{-1}]
p_{t_in}	turbine inlet pressure	[Pa]

The pressure ratio (expansion ratio) is calculated with equation 12:

$$\pi_t = \frac{p_{t\_in}}{p_{t\_out}} \tag{12}$$

π_t	pressure ratio	[-]
p_{t_out}	turbine outlet pressure	[Pa]

Knowing two of these three values, the third value and the turbine isentropic efficiency can be obtained from the turbine map. (Caresana et al. 2014)

In this work, the interdependence between the flow, rotational speed and pressure ratio in the compressor map has been approximated using a modified equation 13 of the ellipse.

$$\left(\frac{x}{a}\right)^z + \left(\frac{y}{b}\right)^z = 1 \tag{13}$$

a	corrected mass flow at pressure ratio zero	[m s $K^{-0,5}$]
b	pressure ratio at zero mass flow	[-]
x	x-axis	[m s $K^{-0,5}$]
y	y-axis	[-]
z	curvature of the curve	[-]

By changing the parameters *a*, *b* and *z*, the shape of the ellipse curve can be adjusted so that it will align closely with the constant speed curves on the compressor map. In the equation, the parameter *a* represents the corrected mass flow at pressure ratio zero, where the curve is crossing the x-axis. The parameter *b* corresponds to the pressure ratio at zero mass flow, where the curve is crossing the y-axis. (Gustafsson 1998)

Similar approach has been used for the turbine map. However, to obtain decreasing nature of the turbine constant speed curves, the original values of turbine pressure ratio have been replaced by values obtained as a subtraction from 5.

Table 6 shows the resulting set of the variables *a*, *b* and *z*, and corrected speed for the ellipsoid equation for modeling the selected constant speed curves on the compressor and turbine maps. Parameters *x*_0 and *y*_0 set the point where the ellipse curve coincides with the constant speed curve. They are used together with *a* and *z* to determine *b*. The values presented below have been obtained at Lappeenranta University of Technology as part of the original model development.

Table 6. Input values for modelling the constant speed curves for compressor and turbine maps.

Parameters	Values			
Compressor map				
Corrected speed [rpm $K^{-0,5}$]	4 228	4 017	3 805	3 382
z [-]	3,10	3,80	5,20	6,50
a [m s $K^{-0,5}$]	$2{,}07 \cdot 10^{-4}$	$1{,}66 \cdot 10^{-4}$	$1{,}42 \cdot 10^{-4}$	$1{,}12 \cdot 10^{-4}$
*x*_0 [m s $K^{-0,5}$]	$1{,}41 \cdot 10^{-4}$	$1{,}29 \cdot 10^{-4}$	$1{,}17 \cdot 10^{-4}$	$9{,}50 \cdot 10^{-5}$
*y*_0 [-]	4,832	4,153	3,685	2,855
b [-]	5,43	4,72	4,02	3,05
Turbine map				
Corrected speed [rpm $K^{-0,5}$]	2 084	1 945	1 806	1 667
z [-]	3,51	3,85	4,16	4,78
a [m s $K^{-0,5}$]	$6{,}71 \cdot 10^{-5}$	$6{,}78 \cdot 10^{-4}$	$6{,}83 \cdot 10^{-4}$	$6{,}85 \cdot 10^{-4}$
*x*_0 [m s $K^{-0,5}$]	$6{,}60 \cdot 10^{-4}$	$6{,}67 \cdot 10^{-4}$	$6{,}73 \cdot 10^{-4}$	$6{,}79 \cdot 10^{-4}$
5 - *y*_0 [-]	1,581	1,704	1,770	1,846
*y*_0 [-]	3,419	3,296	3,230	3,154
b [-]	3,521	3,526	3,567	3,524

These values have been used to approximate the compressor and turbine operation. For intermediate values of speed, linear interpolation has been applied. Figure 12 and Figure 13 show the results of modeling the constant speed curves on the compressor and turbine maps correspondingly, obtained at Lappeenranta University of Technology, using the linear interpolation approach. Red lines in the Figures illustrate the speed curves having an average speed of the adjacent curves map, and yellow lines represent the approximation curves for corrected speeds. Similarly, curves for other average speeds can be calculated.

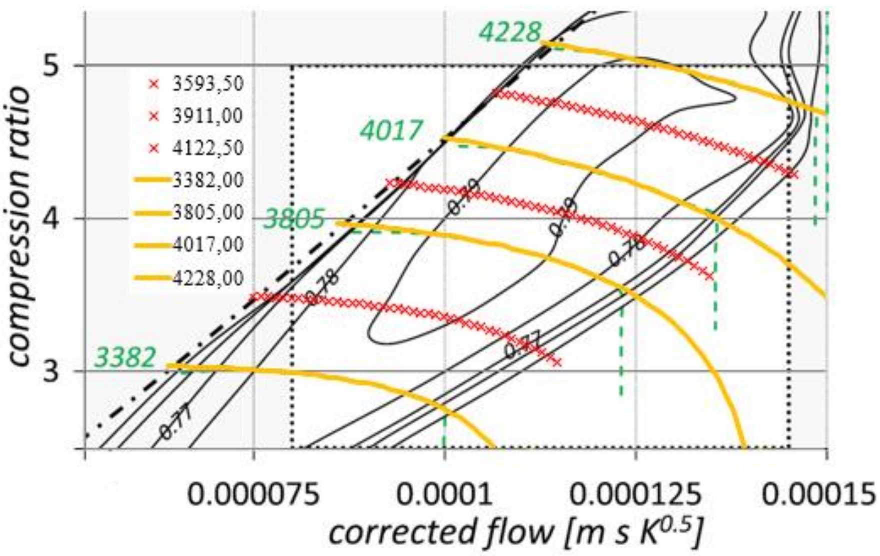

Figure 12. Graphical representation of modelling the curves having an average speed on compressor map.

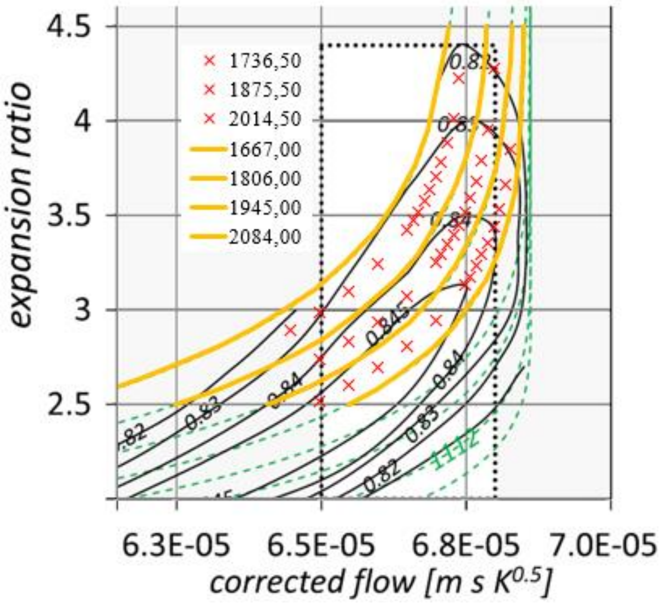

Figure 13. Graphical representation of modelling the curves having an average speed on turbine map.

The above mentioned describes the method to model the interaction between flow, rotational speed and pressure ratio. For the isentropic efficiencies of the compressor and turbine no such approach has been developed, so the efficiency values are given by the user based on the location of the operating points on the maps.

6 SIMULATION RESULTS

6.1 Comparison of manufacturer and calculated values

The aim of this simulation is to compare manufacturer's performance parameters of the Turbec T100 microturbine with calculated parameters of the model in IPSEpro software. Due to its configuration, the T100 generates combined heat and power with high overall efficiency. The hot gases exiting the turbine are used for hot water production. The standard performance parameters of Turbec T100 microturbine are calculated for new and clean unit working at ISO standard conditions and utilizing natural gas with fuel lower heating value of 39 [MJ/m_n^3]. The input conditions are shown in Table 7.

Table 7. Input conditions for Turbec T100 (Turbec 2009).

Site elevation [m above sea level]	0
Ambient temperature [°C]	15
Relative humidity [%]	60
Pressure drop to air inlet flange [Pa]	0
Pressure drop from exhaust gas flange [Pa]	0

According to the manufacturer data, at ISO standard conditions and at the nominal rotational speed of 70 000 rpm, the unit generates 100 kW of electrical power with an efficiency of 30 percent, the combustion gases enter the turbine at a temperature of 950 °C and exit the turbine at 650 °C, then go through the recuperator, and the recovery heat exchanger. The microturbine can safely operate at ambient inlet temperature from minus 25 °C to 40 °C with a maximum electric power output of 120 kW. At nominal condition the specified heat output of the recovery heat exchanger is approximately 165 kW. (Turbec 2002)

As it was mentioned above, the performance of the microturbine model in IPSEpro system can be simulated with design and off-design parameters. Taking into consideration the ISO standard conditions, general assumptions, and equations, the IPSEpro microturbine model has been created. At design operating point, the compressor pressure ratio and mass flow as well as the efficiency of the components have been selected on the basis of compressor and turbine maps.

Firstly, the model with design-point operating values is simulated and the results of this simulation are compared with the manufacturer values. Then, microturbine model with off-design input values is simulated and presented below. In the following Figure 14 the symbols and notations, used in the IPSEpro model, are illustrated. The model with design operating-point values is illustrated in Figure 15.

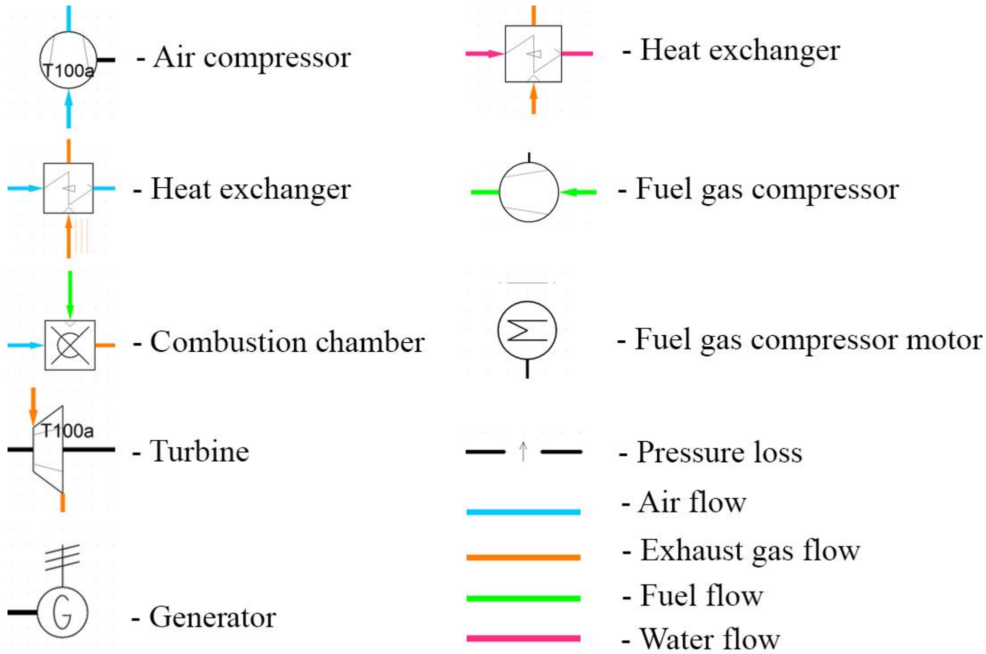

Figure 14. The symbols and notations used in the IPSEpro model.

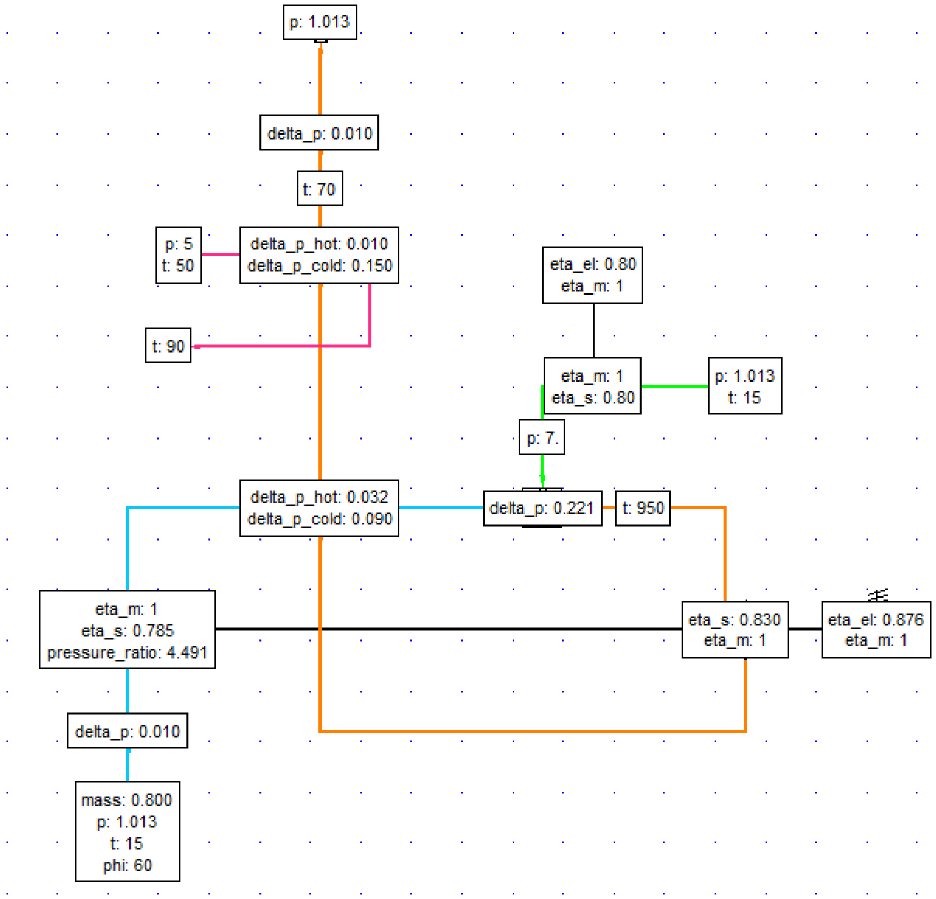

Figure 15. The microturbine model with design-point values.

The processes that occur in the microturbine model can be described with air-combustion gas path. The ambient air at a temperature of 15 °C, relative humidity 60 % and pressure 1,013 bar goes to the compressor. The pressure ratio of the compressor is 4,491. During the compression, air temperature and pressure increase. In the recuperator compressed air is preheated by the exhaust gas from the turbine. The recuperation ratio of the recuperator is 0,850. In the combustion chamber the preheated compressed air mixes with the gaseous fuel and heat is released during combustion. The gases exit from the combustor at a temperature of 950 °C and enter the turbine. Due to the expansion of combustion gases through the turbine, the temperature and pressure decrease. After the recuperator, the exhaust gas enters the recovery heat exchanger. The heat from the exhaust gas is used for water heating in the recovery heat exchanger. It is a counter-flow type with water inlet temperature of 50 °C and water outlet temperature of 90 °C. The amount of generated heat is directly related to the amount of generated electric power. The exhaust gas outlet temperature is 70 °C. The fuel enters at a pressure of 1,013 bar, it is increased in the fuel gas compressor to 7 bar. The component efficiencies and pressure losses are given in Table 8.

Table 8. Design-point efficiencies and pressure losses in the microturbine model. The pressure losses are given relative to the corresponding inlet pressure.

Component	Efficiencies [-]	Component	Pressure losses [%]
Compressor	0,785	Inlet	1
Turbine	0,830	Recuperator cold side	2
Generator	0,876	Combustion chamber	5
Fuel gas compressor	0,800	Recuperator hot side	3
Fuel gas compressor motor	0,800	Exhaust gas heat exchanger hot side	1
		Outlet	1

Figure 16 presents the simulation results with design-point operating values using natural gas.

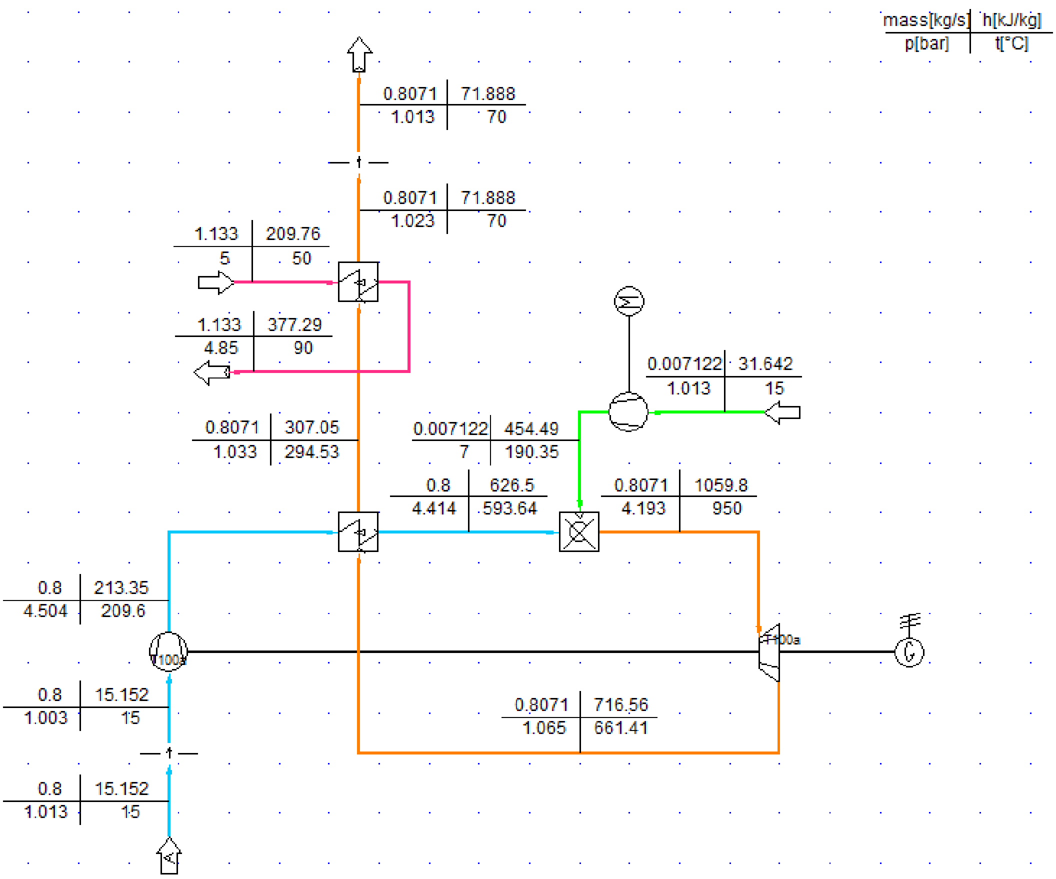

Figure 16. The microturbine model with design-point values using natural gas.

Table 9 presents the manufacturer performance parameters using low-pressure natural gas and calculated performance parameters in IPSEpro software using natural gas.

Table 9. Performance characteristics of Turbec T100. Manufacturer data from (Turbec 2009).

Performance parameters	Manufacturer	IPSEpro
Electrical output [kW]	100 (±3)	100,0
District heating output [kW]	165 (±5)	189,8
Fuel input [kW]	333,0	354,1
Electrical efficiency [%]	30 (±1)	28,2
Total efficiency [%]	80 (±1)	82,9
Turbine inlet temperature [°C]	950	950
Exhaust gas outlet temperature [°C]	70	70
Exhaust gas flow [kg s^{-1}]	0,800	0,807

In the IPSEpro model, the generator efficiency was selected so that the net electric output is 100 kW. As it can be seen in Table 9, manufacturer performance parameters differ from calculated in the IPSEpro software. This results from the simplifications in the model. One contributing factor is that the IPSEpro model assumes no heat losses. The chemical composition of natural gas also differs slightly from the manufacturer fuel, but this has a lesser effect on the performance. During the simulation, the natural gas in the Danish grid was used as a fuel.

The model with off-design operating-point values is illustrated in Figure 17.

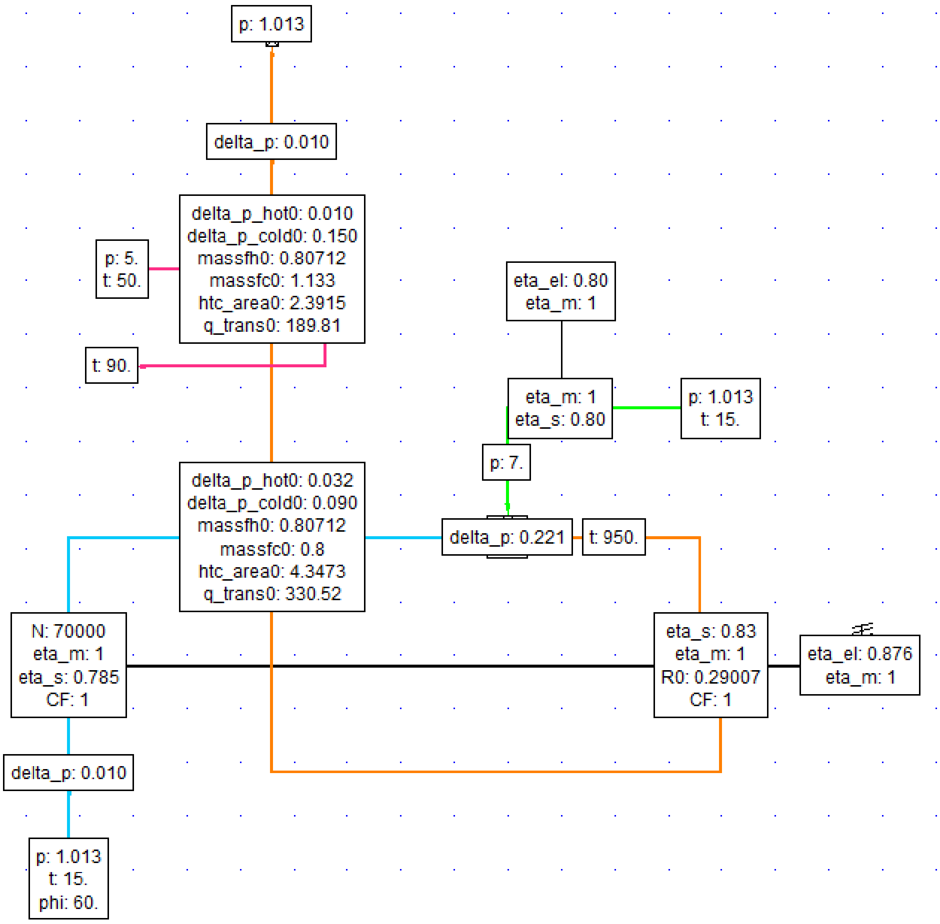

Figure 17. The microturbine model with off-design-point values.

In off-design model, the interaction between mass flow, pressure ratio and rotational speed are determined by using maps, which have been approximated using the modified equation of the ellipse. During the simulation, the compressor and turbine efficiencies are obtained manually from the maps and set as an input values to the model by the user. The conductance of the recuperator and exhaust gas heat exchanger is assumed to be constant and have the design-point value. The heat transfer rate is determined by the conductance and the logarithmic mean temperature difference. The inlet and outlet pressure losses (0,010 bar) and pressure losses in the combustion chamber (0,221 bar) are set as constant values, meanwhile the pressure losses of the recuperator and exhaust gas heat exchanger are relative to square of mass flow rate.

Figure 18 illustrates the off-design performance using natural gas.

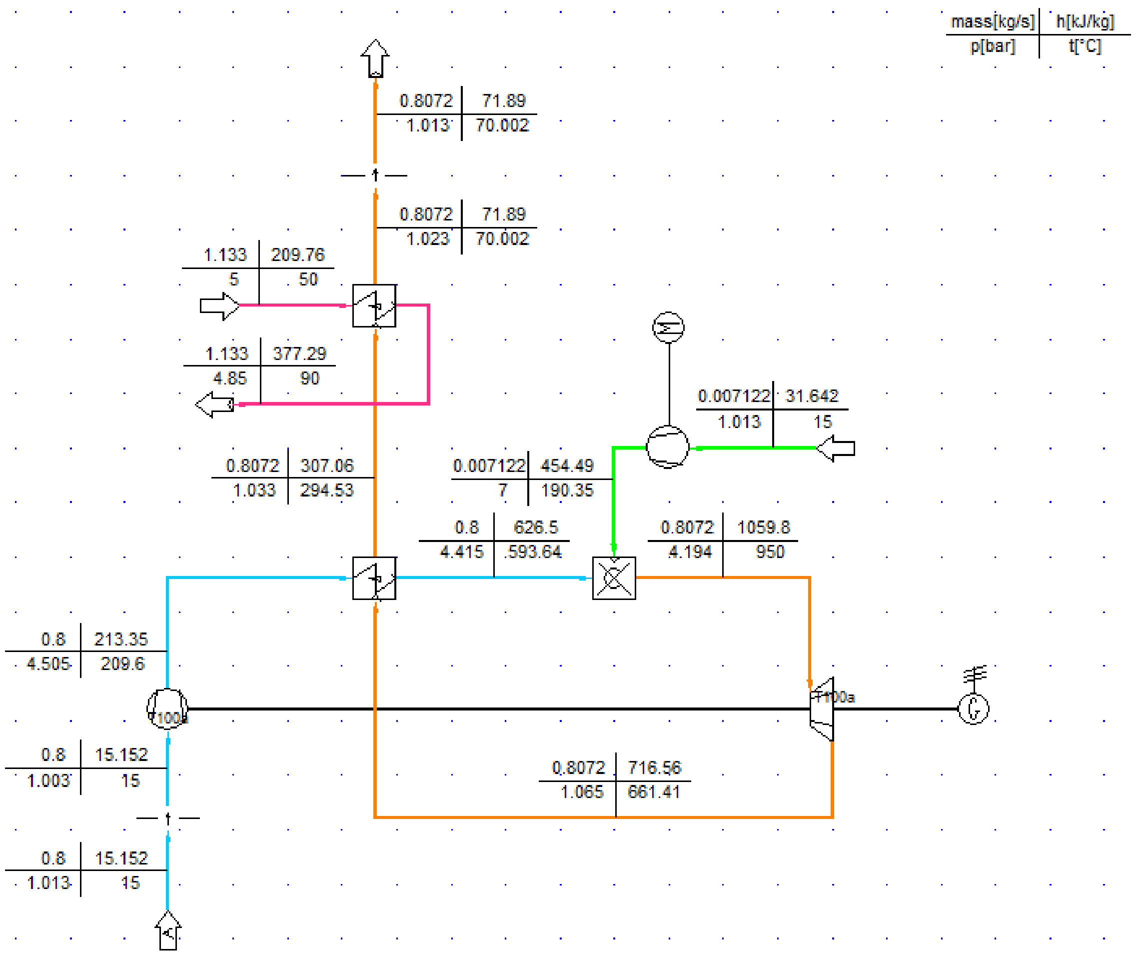

Figure 18. The microturbine model with off-design-point values using natural gas.

6.2 Effect of fuel composition

The aim of this simulation is to compare performance parameters of the IPSEpro microturbine model using natural gas, biogas from anaerobic digestion and landfill gas. During the simulation with these fuels, the input values shown in Figure 17 are kept constant. The exceptions are the compressor and turbine efficiencies, which are altered if necessary.

In order to compare the compressor and turbine efficiencies of the microturbine model between different fuels the pressure and expansion ratio, and corrected flow are calculated by the software. These parameters are then used to plot the operating points on the corresponding maps. Table 10 presents the pressure and expansion ratio and corrected flow.

Table 10. Results of simulations of microturbine using different fuels.

	Parameter	Natural gas	Biogas from AD	Landfill gas
Compressor map	Pressure ratio [-]	4,491	4,497	4,504
	Corrected flow [m s $K^{-0,5}$]	$1,354 \cdot 10^{-4}$	$1,351 \cdot 10^{-4}$	$1,346 \cdot 10^{-5}$
Turbine map	Expansion ratio [-]	3,938	3,943	3,949
	Corrected flow [m s $K^{-0,5}$]	$6,732 \cdot 10^{-5}$	$6,731 \cdot 10^{-5}$	$6,732 \cdot 10^{-5}$

The operating points using different fuels are plotted on the graphs of compressor and turbine maps in Figure 19, which are zoomed for better visibility.

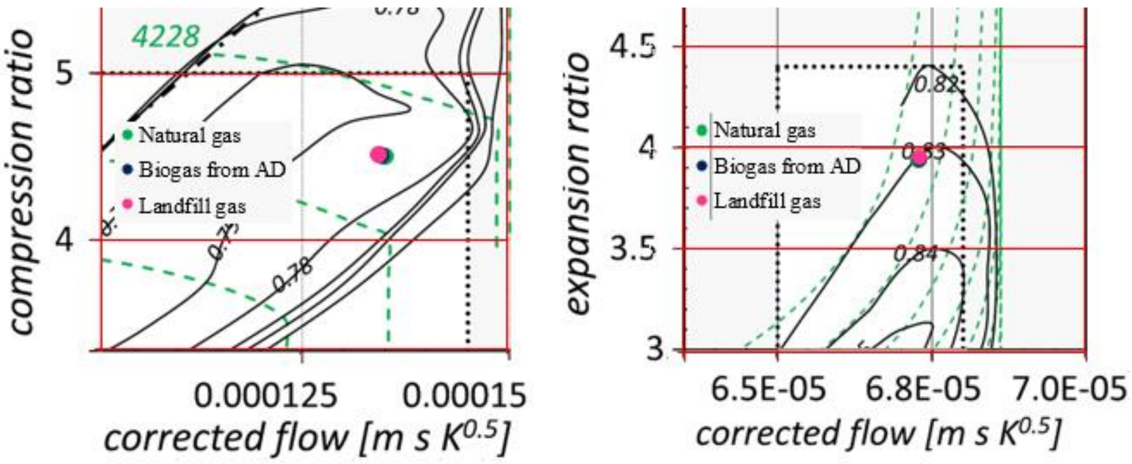

Figure 19. Operating points on the compressor map (left) and turbine map (right).

It can be seen, that the operating points are located extremely close to each other, thus the compressor efficiencies of the microturbine model at the nominal operating conditions using different fuels are nearly identical, the same is true for the turbine efficiencies. The compressor efficiencies equal to 0,785 and the turbine efficiencies are 0,830. The general results of the simulation are shown in Table 11.

Table 11. Results of model simulation using different fuels.

	Natural gas	Biogas from AD	Landfill gas
Net electric output [kW]	100,0	99,7	99,1
District heating output [kW]	189,8	191,2	192,6
Fuel input [kW]	354,1	356,5	359,4
Generator output [kW]	103,8	104,5	105,5
Fuel gas compressor motor input [kW]	3,8	4,7	6,4
Net electric efficiency [%]	28,2	28,0	27,6
Total efficiency [%]	82,9	82,9	82,9
Lower heating value [kJ kg^{-1}]	49 261	32 528	23 719

The higher is the lower heating value of the fuel, the higher is the net electric output and net electric efficiency. However, district heating output decreases with increasing of LHV of the fuel. Lower heating value directly influences on the fuel mass flow rate. The lower is methane content of the fuel, the higher is the fuel flow and, consequently, exhaust gas flow and generator output, but also fuel gas compressor motor input. As a result, the net electric output is decreased. Total efficiency of the system remains approximately the same with very little change.

6.3 Effect of electric output regulation and ambient temperature

The aim of this simulation is to investigate the effect of rotational speed, turbine inlet temperature and ambient temperature on the microturbine performance. In the previous simulations, the ambient temperature was 15 °C, however in real life this temperature can differ from ISO conditions. Ambient pressure and relative humidity vary too, but they have a lesser effect on the operation and, therefore, are omitted from this study. During this simulation, biogas from anaerobic digestion is used. It is chosen as a fuel because it is a renewable source of energy and usage of renewable fuels is supported in the European Union. In central Europe, the number of biogas plants has increased in the recent years. Most of them utilize agriculture feedstocks and future trend in Europe is the increasing growth of the number of agriculture biogas plants. (European Biogas Association Report 2015)

During the simulation, the rotational speed is decreased from 70 000 rpm to 58 300 rpm and turbine inlet temperature from 950 °C to 860 °C. Values of 58 300 rpm and 860 °C are selected as lowest possible in this case due to limitations in the approximation area. According to the manufacturer the microturbine can safely operate at ambient inlet temperature from minus 25 °C to 40 °C. (Turbec 2002). However, with ambient temperature range from minus 25 °C to 0 °C the operation cannot be simulated due to the map limitations. Thus, the effect of ambient inlet temperature is investigated from 1 °C to 40 °C.

The operating points are plotted on the compressor and turbine maps, in Figure 20 and Figure 21 correspondingly. Orange circles represent speed control with constant turbine inlet temperature (TIT) of 950 °C and ambient temperature (T_{amb}) of 15 °C. Green circles represent turbine inlet temperature control with constant rotational speed (N) of 70 000 rpm and T_{amb} of 15 °C. Pink circles represent variation of ambient temperature with constant N of 70 000 rpm and TIT of 950 °C. Black dot is the nominal design operating point with rotational speed of 70 000 rpm, TIT of 950 °C and ambient temperature of 15 °C.

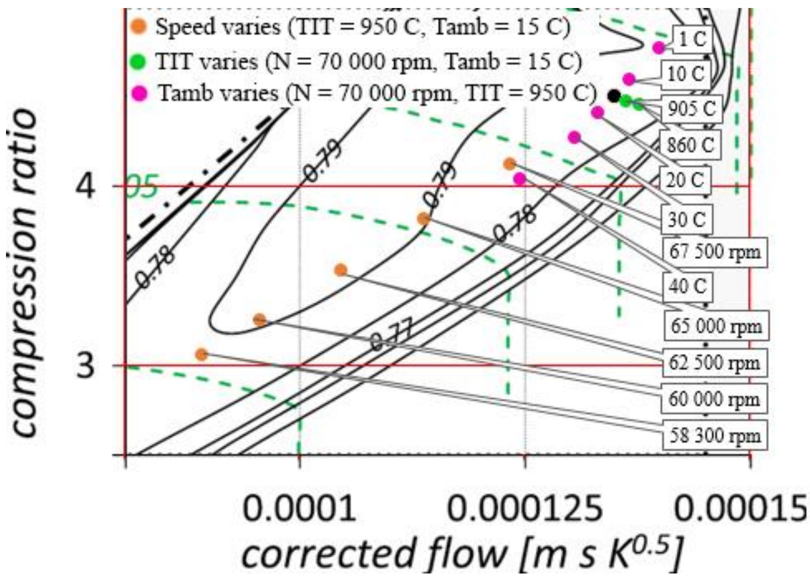

Figure 20. Operating points at varying conditions on the compressor map.

Ambient conditions influence on the microturbine performance since the air density is different with different temperatures. When the ambient temperature decreases, the air density increases, thus the mass of the air which enters the compressor increases. At the same time, the pressure ratio of the compressor increases, increasing the specific power (thermal power divided by the compressor mass flow rate). These are the main contributing factors to the power increase. For the studied case, decrease in ambient temperature also leads to the compressor efficiency decrease and turbine efficiency increase.

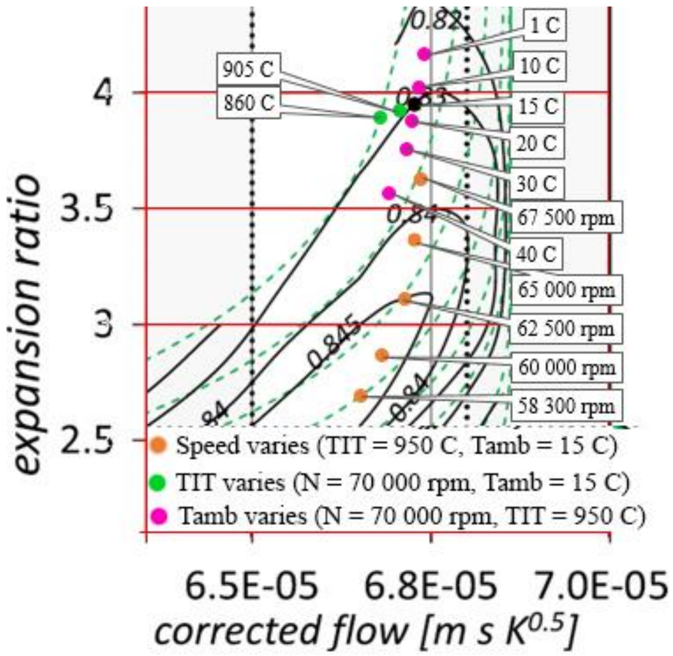

Figure 21. Operating points at varying conditions on the turbine map.

The microturbine output can be regulated by varying the rotational speed and turbine inlet temperature. The current way for microturbine output regulation is speed control. It is predominantly used in real life applications, because it maintains the part load efficiency better. In this work, TIT control is used for making comparison. The results of these methods of output control are plotted in Figure 22 and Figure 23. Orange lines represent the speed of rotation control with constant TIT of 950 °C, green lines – turbine inlet temperature control with constant rotational speed of 70 000 rpm and black dots represent the nominal operating points with rotational speed of 70 000 rpm and TIT of 950 °C. All values are calculated at ambient temperature of 15°C.

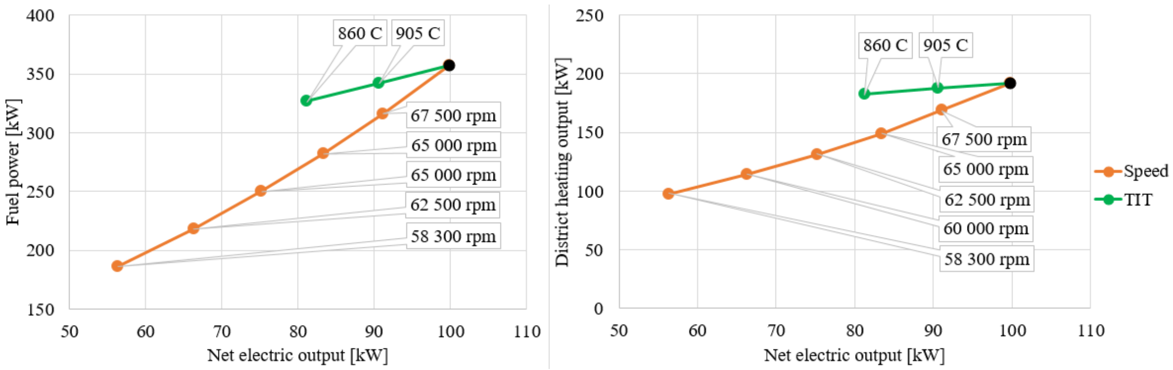

Figure 22. Effect of output control on the fuel and district heating power.

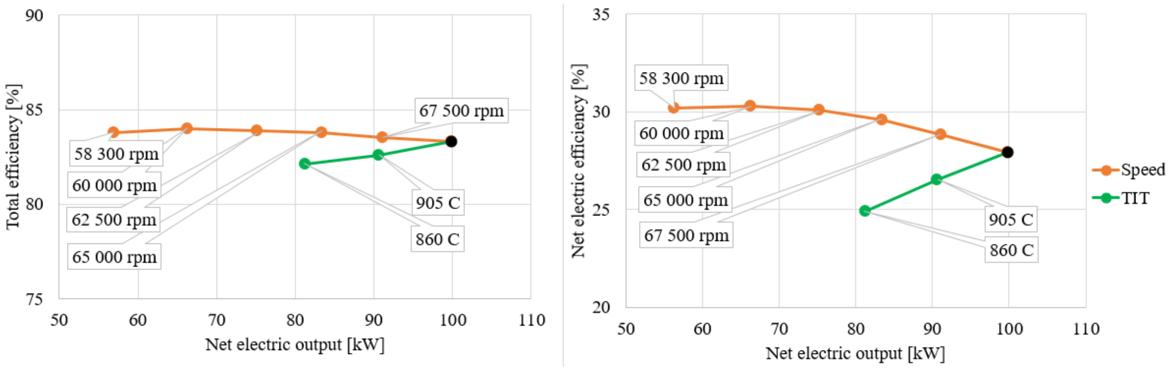

Figure 23. Effect of the microturbine output control methods on the efficiencies.

As it can be seen in the Figures above, higher turbine inlet temperature yields higher total and net electric efficiencies. With decreasing TIT, the efficiencies decrease significantly. However, with the speed decreasing, total and net electric efficiencies have a tendency to increase, which is due to increasing compressor and turbine efficiencies as well as increasing recuperation ratio of the recuperator. By using speed control, the load can be regulated at wider range than with TIT control in the studied case with limitations in the approximation area.

As the net electric output is decreased from 100 kW, the modelled net electric efficiency has first similar increasing trend as efficiency obtained from the manufacturer correction curve in Figure 7. However, the modelled efficiency continues to increase while according to the manufacturer, efficiency starts to decrease below 90 kW. One contributing factor for this may be that TIT is maintained constant in the model, while in the real microturbine it is decreased to prevent too high exhaust gas temperatures at the recuperator inlet.

7 CONCLUSIONS AND SUMMARY

There is a growing trend towards decentralized heat and electricity generation. Micro combined heat and power (micro-CHP) plants have been recognized by the European Union as having a great potential to improve energy efficiency and reduce carbon dioxide emissions. In this thesis, the performance of CHP with the microturbine as a prime mover has been studied. A model is used that has been developed for the microturbine using a heat balance modeling software IPSEpro. Special attention is given to the operation using biofuel, as the share of renewable energy for heat and power generation is projected to grow in years ahead. Fuel properties, characteristics of the CHP with microturbine and current situation in European energy sector are studied through a comprehensive literature review.

The main objective of this work is to provide information about the microturbine Turbec T100 (currently AE-T100 from Ansaldo Energia) performance at varying operating conditions, such as fuel composition, rotational speed, turbine inlet temperature and ambient temperature on the basis of an IPSEpro model. The microturbine model has been constructed with a reasonable degree of complexity. However, some simplifications have been made that relate to the internal flows and heat losses of the engine, the power need of the auxiliary systems, and the combustion process. The model can be used for simulating varying operating conditions of the similar microturbine units.

The practical part contains three simulations. The aim of the first simulation is to compare manufacturer performance parameters of the Turbec T100 microturbine with calculated parameters of the model in IPSEpro. The model with design-point operating values is simulated. Obtained results differ from the manufacturer data due to the simplifications in the model. One contributing factor is the omission of the heat losses.

The goal of the second simulation is to compare performance parameters of the microturbine model using natural gas, biogas from anaerobic digestion and landfill gas. According to the results, the compressor efficiencies of the microturbine at the nominal operating conditions using different fuels are nearly identical, and the same is true for the turbine efficiencies. The lower heating value of the fuel has a direct influence on the performance parameters. The higher is the methane content of the fuel, the higher is the net electric output and net electric efficiency. However, district heating output decreases with increasing of LHV of the fuel. Total efficiency of the system remains approximately the same with very little change.

The target of the third simulation is to investigate the effect of rotational speed, turbine inlet temperature and ambient temperature on the microturbine performance. During this simulation, biogas from anaerobic digestion is used as a fuel. According to the results, when the ambient temperature decreases, the mass of the air which enters the compressor increases. At the same time, the pressure ratio of the compressor increases, increasing the specific power (thermal power divided by the compressor mass flow rate). These are the main contributing factors to the power increase. For the studied case, decrease in ambient temperature also leads to the compressor efficiency decrease and turbine efficiency increase.

The microturbine output can be regulated by varying the rotational speed and turbine inlet temperature. Higher turbine inlet temperature yields higher total and net electric efficiencies. With decreasing turbine inlet temperature, the efficiencies decrease significantly. However, with the rotational speed decreasing, total and net electric efficiencies have a tendency to increase, which is due to increasing compressor and turbine efficiencies as well as increasing recuperation ratio of the recuperator. By using speed control, the load can be regulated at wider range than with turbine inlet temperature control in the studied case with limitations in the approximation area. At part load, the behavior of the modelled net electric efficiency differs from the manufacturer data. One contributing factor for this may be that turbine inlet temperature is maintained constant in the model, while in the real microturbine it is decreased to prevent too high exhaust gas temperatures at the recuperator inlet.

For future research, the microturbine model can be developed further for higher accuracy. The combustion process can be detailed in order to calculate the emissions. It will be interesting to investigate the operation with low methane content fuels.

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