Best practise report on decentralized biomass fired CHP plants and status of biomass fired small- and micro scale CHP technologies

Steam piston engine BISON, Button Energy Energiesysteme GmbH, Wiener Neudorf (A), tested in 2009 by BIOENERGY 2020+ GmbH, Graz (A)

IEA Bioenergy

IEA Bioenergy: Task 32: February 2019

Best practise report on decentralized biomass fired CHP plants and status of biomass fired small- and micro scale CHP technologies

Reinhard Padinger

Stefan Aigenbauer

Christoph Schmidl

Contribution to the outlook section: Jens Dall Bentzen, Dall Energy, Hørsholm, Denmark

Copyright © 2019 IEA Bioenergy. All rights Reserved

Published by IEA Bioenergy

IEA Bioenergy, also known as the Implementing Agreement for a Programme of Research, Development and Demonstration on Bioenergy, functions within a Framework created by the International Energy Agency (IEA). Views, findings and publications of IEA Bioenergy do not necessarily represent the views or policies of the IEA Secretariat or of its individual Member countries.

Contents

1 Introduction

A combined heat and power (CHP) plant is a facility for the simultaneous production of thermal and electrical resp. mechanical energy in one process. As compared to power plants, the overall process efficiency is higher as the otherwise rejected heat is also transferred to consumers.

Biomass CHPs are operated with different kinds of solid-, gaseous- as well as liquid fuels or residues. There are various processes for the production of power and heat from biomass, and some 1,000 facilities were operational in EU28 in 2016 [128]. Most commonly they are based on either biomass combustion or anaerobic digestion.

The principal paths of biomass feedstocks to heat and power are shown in Figure 1 [130].

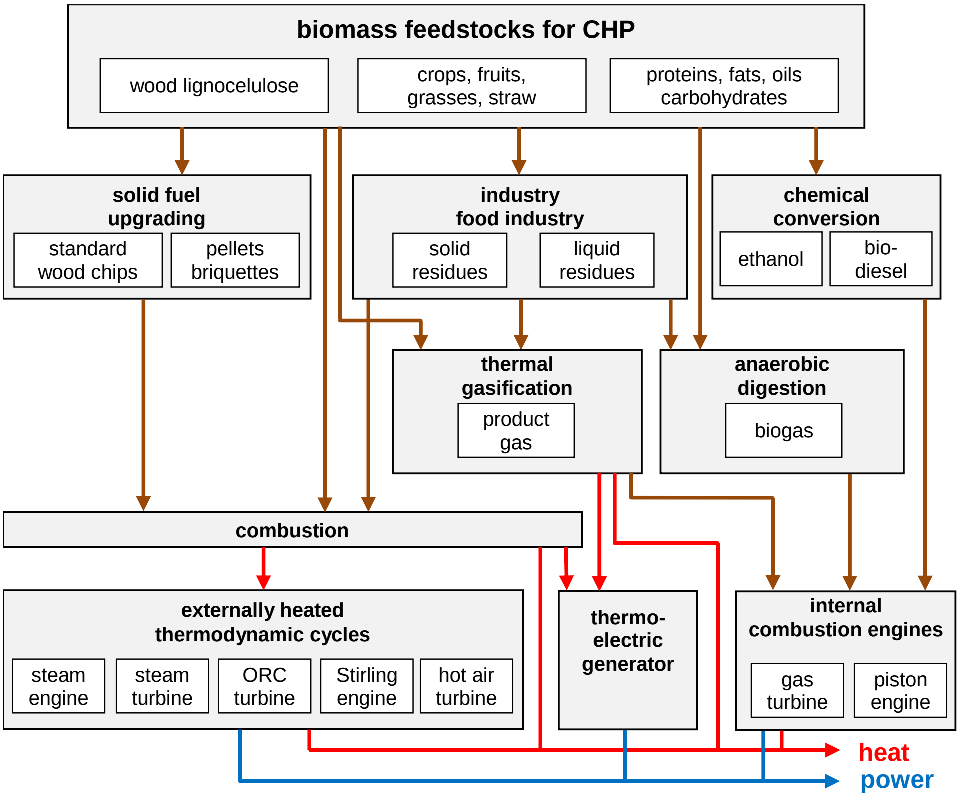


Figure 1: principal paths of biomass feedstocks to CHP [130]

Solid fuels are wood resp. lignocellulose materials but also other crops, as they are grasses or fruits as well as more or less every other organic residue. A lot of solid fuels can be directly fired in a combustion unit, producing heat in a first step which powers a thermodynamic cycle resp. an externally heated engine. Advanced combustion technologies make sure, that the relevant environmental requirements concerning harmful emissions are fulfilled.

Under certain circumstances, it may be better to gasify the solid feedstock at first and use the product gas as a gaseous fuel. Gasification is possible via thermal processes, leading to product gases with a certain heating value due to a higher content of carbon monoxide or hydrocarbons, or even – especially in case of wet feedstocks – via anaerobic fermentation, leading to biogas with methane as the main energy source. Gaseous fuels can be after cleaning directly used in gas turbines and internal combustion engines. Liquid fuels, which are produced via chemical conversion for use as an energy source, e.g. biodiesel from rape seed or ethanol as a base material for the production of different other biofuels, are normally not used in stationary applications due to their high value as a fuel for motor vehicle resp. mobile applications. However a wide spectrum of solid and liquid industrial residues – black liquor, molasses, stillage, vinasse, sugar compounds, and others – are used for CHP.

The role of biomass CHP in the EU is shown in

Figure 2, which has been prepared based on data of the actual AEBIOM Statistical Report [127].

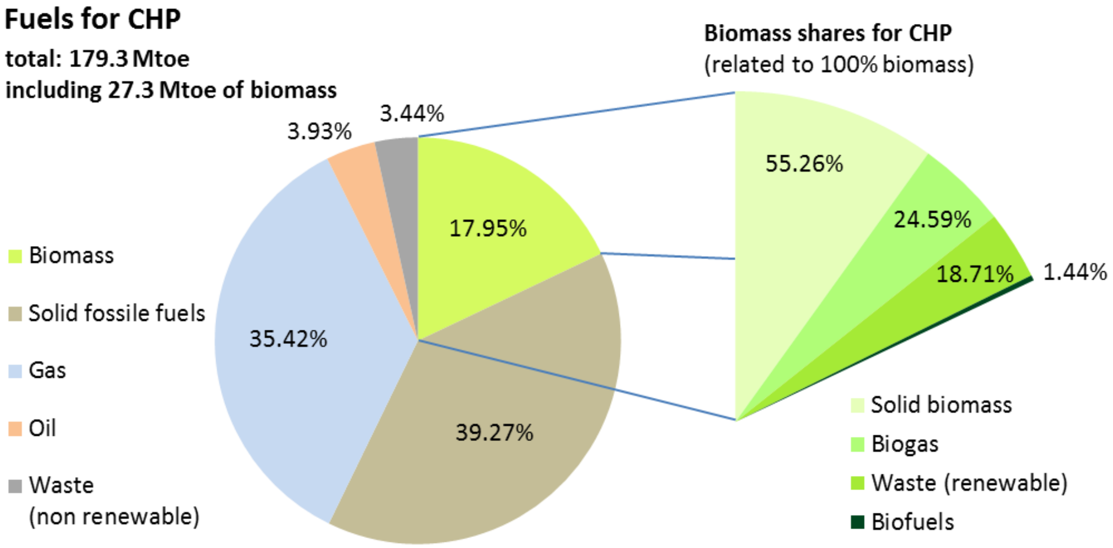


Figure 2: fuels and biomass shares for CHP in EU28 (status 2014 [127])

As shown in Figure 2 biomass contributed in 2014 to the CHP production in the Europen Union with 27.3 Mtoe, which is 17.95 % of the total CHP production of 179.3 Mtoe.

Applications range from very small appliances for domestic use, so called "micro scale CHPs" in the range till 50 kW$_e$ via "small scale CHPs" for larger buildings and local heating grids to "medium-" and "large scale CHPs" for industrial sites or district heating grids. CHPs, driven with biomass only, range up to some 20 MW$_e$. Biomass however contributes also in larger CHPs to co-generation with fossile fuels – mostly coal – up to 500 MW$_e$. Depending on the application different technologies are being used. Typical electric capacities for various applications are listed in Table 1 together with the preferred technologies.

Table 1 shows also the differentiation of the terminology in language usage between "micro scale" application till some 50 kW$_e$, "small scale" applications from 50 to 1,000 kW$_e$, and "medium-" and "large scale" applications" as shaded in Table 1. CHP plants, driven by biomass only, range up to some 30 MW$_e$. Biomass however also contributes in larger CHP plants to co-firing with fossile fuels – mainly coal – up to 300 MW$_e$.

Table 1: biomass CHP applications and preferred technologies in different power ranges

terminology	power range	typical application	preferred technology
micro scale CHP	0.01 - 0.5 kW$_{el}$	domestic appliances special appliances	thermoelectric generators
	0.5 - 50 kW$_{el}$	single family houses semidetached houses small and medium enterprises farms	micro steam engines micro ORC applications Stirling engines
small scale CHP	50 kW$_{el}$ - 1 MW$_{el}$	multiple dwelling hotels local heating grids	steam engines ORC applications thermal gasification or anaerobic fermentation with gas piston engines
medium and large scale CHP	1 - 10 MW$_{el}$	hospitals commercial enterprises regional heating grids	ORC plants (< 6 MW$_{el}$) steam engines steam turbines
	10 - 30 MW$_{el}$	city heating grids industrial site	steam turbines gas turbines
	30 - 300 MW$_{el}$	district heating grids	steam turbines, co-firing with fossil fuels

The subject study focuses on small- and micro scale CHP technologies as shown in the non-shaded section of Table 1.

For the most relevant technologies as they are steam engines, ORC applications, Stirling engines, and thermoelectric generators, the most important technical parameters together with operational results and experiences as well as boundary conditions for application are described and presented in form of fact sheets. Technology developments in the last 10 years are summarized and further R&D needs are specified. For each technology also selected monitoring data are presented and discussed.

Best practise reports on small scale CHP plants including 6 case studies with twin screw steam expander technology, as well as further 3 case studies with micro-expander technology are presented. Possible optization measures and recommendations for further applications have been derived.

In the outlook section, recent experiences with hot air turbines as a possible relevant small scale CHP technololgy in the near future are described and a contribution of Jens Dall Bentzen, Dall Energy, Hørsholm, Denmark concering the optimization of combutions plants in the viewpoint of small scale CHP has been included.

2 Status of biomass fired micro scale CHP technologies

2.1 General information

With small and micro scale CHP it is possible to achieve energy efficiency, by converting primary energy to heat and electricity in small scale applications like households or residential sector. Energy losses are minimized because heat losses at central electricity production facilities and network losses in the electricity grid are avoided. Micro-CHP products produce heat and electricity simultaneously based on a range of technologies [27]. They can be categorized in three groups: external heat input (or external combustion) technologies, internally fired (or internal combustion) technologies and chemical conversion technologies (fuel cells).

Although some micro-scale CHP technologies are primary used to convert fossil fuels, like the Internal combustion engine (ICE) and micro gas turbine it is also possible to use every technology also for renewable energy resources. The use of solid renewable primary energy like wood, requires further conversion technologies like gasification, fermentation or reformation of biomass. Figure 3 gives an overview of micro-scale CHP technologies up to 50 kW_e.

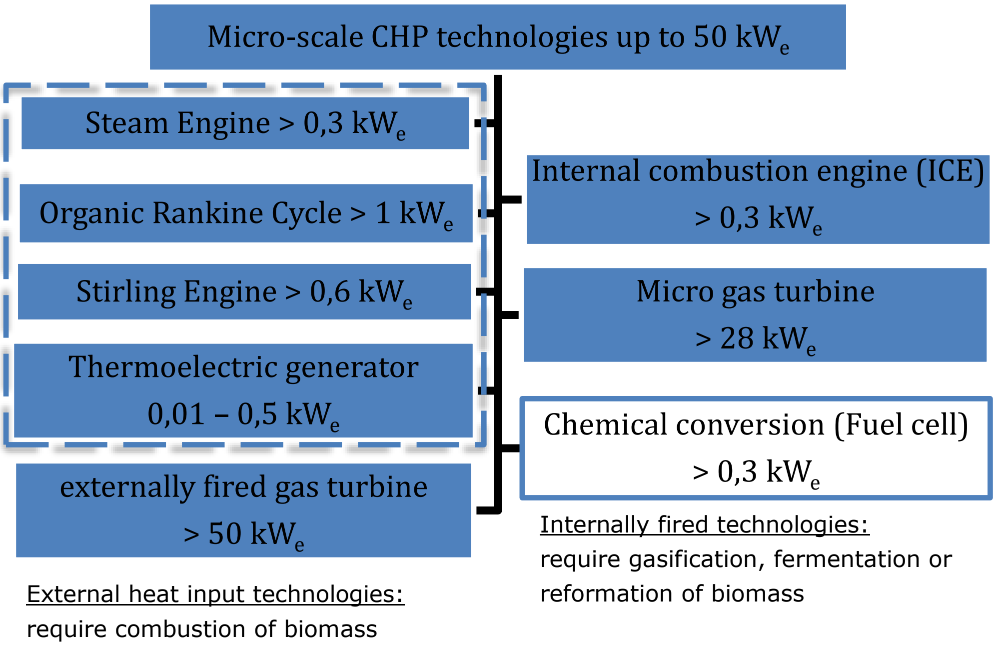


Figure 3: classification of Micro-scale CHP technologies and investigated technologies of the present study (dashed line sector)

The present study focus following externally fired micro-scale CHP technologies in the power range up to 50 kW_e: steam engine, organic Rankine cycle, Stirling engine and thermoelectric generator.

The development of micro-CHP systems is in an early phase of commercialisation. In the residential sector, electrical capacities are up to 5 kW_e and heat capacity depending on technology up to 20 kW_{th}. In the SME & collective sector, gas engine systems of capacities from 5 to 50 kW_e resp. 2,5 to 250 kW_{th}, are used, with over 100,000 systems already installed [27].

A report, which has been developed in the frame of the CODE2 project [75], estimates the potential for annual sold micro-CHP systems in the EU for residential applications (0.1 - 5 kW_e) of about 2,900,000 and for SME and collective applications (5 - 50 kW_e) of about 68,000 units in 2030. It is assumed that a cost-competitive price would be around €3,000 per kW_e for a household system. However at this moment (2018) the technology is still too expensive for mass market introduction, approximately €8,000.- per kW_e for Stirling/combustion engines and €20,000.- per kW_e for fuel cells [27]. In Figure 4 it can be seen that according the CODE2 micro-CHP potential and market analysis a price level of around €3,000.- per kW_e (retail price €4,000.- per kW_e) can be expected in 2025 with around 250,000 units being sold per year [27].

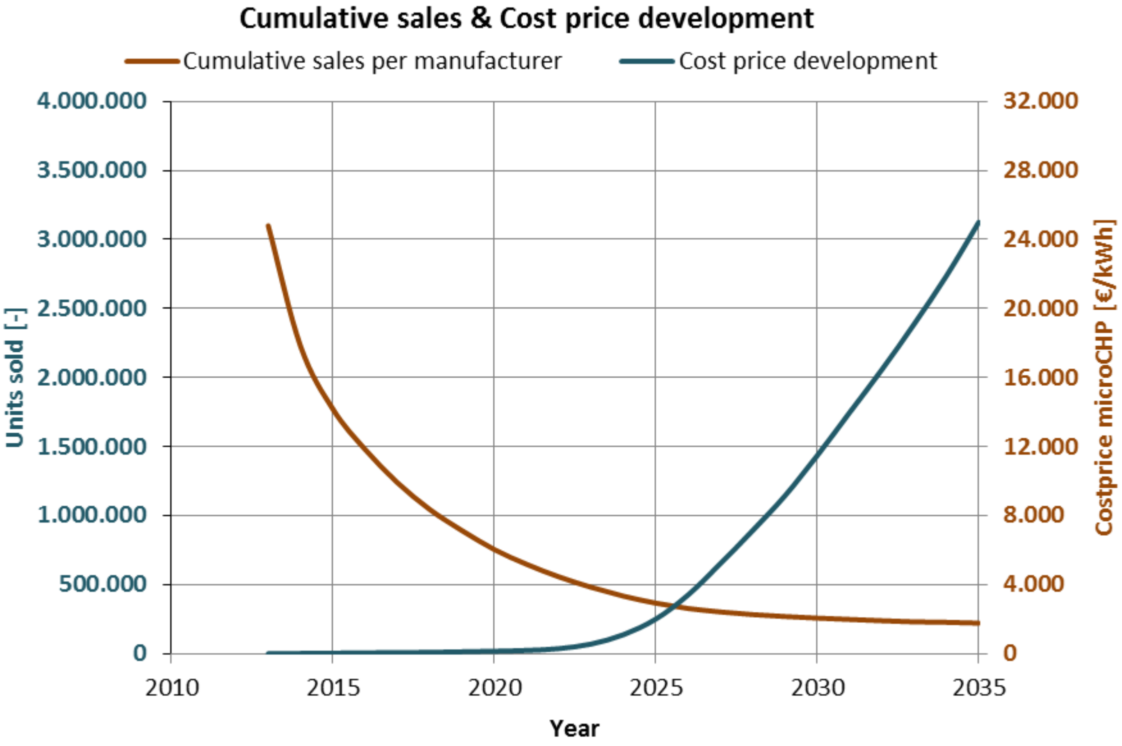


Figure 4: **cumulative sales per manufacturer versus cost price development at 15 % learning rate starting with €25.000 per kW_e and low volumes of 10 units per year [27]**

The electrical efficiency of a certain power plant can be defined as the electrical power output (P_e) divided by the chemical energy stored within the fuel at the entrance of the power plant, which can be obtained, in turn, multiplying the LHV of the fuel by the amount of fuel required for the generation of electricity [3].

$$\eta_e = \frac{P_e[KW_e]}{LHV \left[\frac{kJ}{kg}\right] * \dot{m}[kg/s]}$$

The total efficiency includes the thermal output of CHP plants (Q_{th}). Thereby, it can be calculated as follows [3]:

$$\eta_{tot} = \frac{P_e[KW_e] + Q_{th}[KW_{th}]}{LHV\left[\frac{kJ}{kg}\right] * \dot{m}[kg/s]}$$

Current efficiencies of selected technologies of biomass based micro CHP:

Electrical efficiencies of micro-scale plants are between 13 % and 25 % [3]; [85]; [86]; [87] - [92] and total efficiencies between 60 % and 74 % [3]; [89]; [91]. At micro-scale, 25 – 30 % is the current technological limit of biomass conversion to electricity efficiency [3]. Figure 5 shows the electrical efficiencies of biomass conversion technologies which have been reached in the different power ranges.

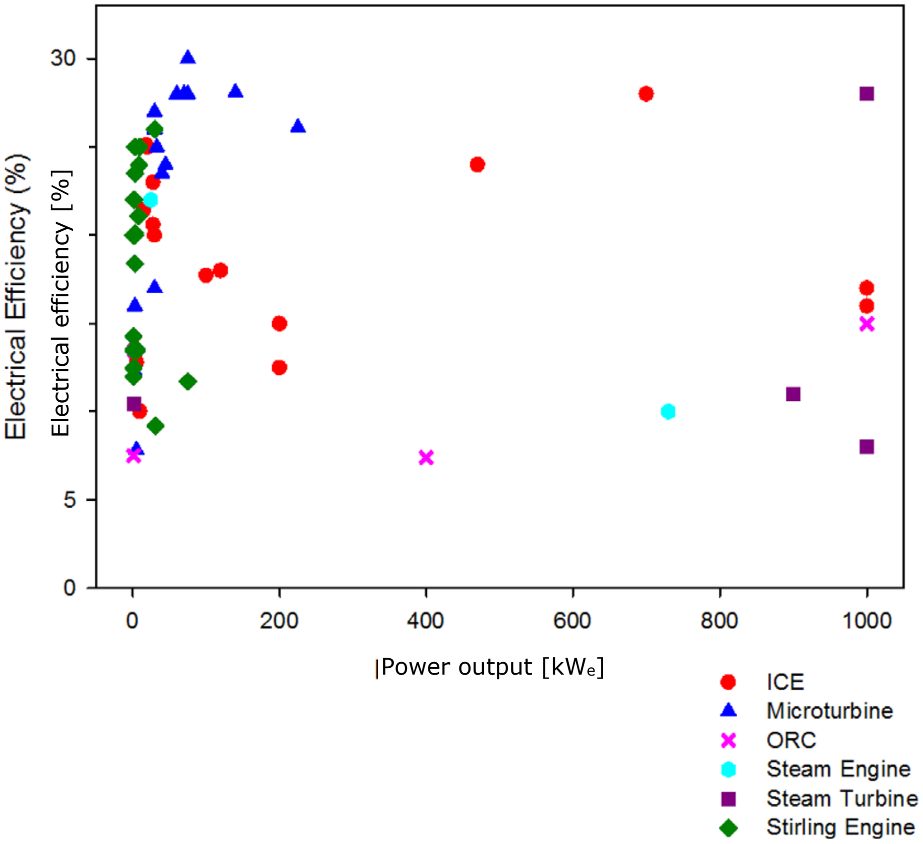


Figure 5: Electrical efficiencies of biomass conversion technologies [3]

Table 2 gives an oveview about the range of the basic technical parameters of different micro scale CHP technologies driven by solid biomass together with the investment costs and the current status of development as published in different papers.

Table 2: Overviev about micro scale CHP technologies driven by solid biomass

Micro-scale CHP technologies	el. power [kWe]	overall efficiency [%]	el. efficiency [%]	Investmentcosts [€/We]	Development status
Steam Engine	> 0.3 - 60	70 - 95	10 - 25	3 – 9.5	> 10 kW_e: Commercialisation < 10 kW_e: R&D [47],[6],[115],[116]
Organic Rankine Cycle	0.3 - 50	60 - 83	3.5 - 15	1 - 6	> 10 kW_e: Commercialisation < 10 kW_e: R&D [121],[20],[28],[124],[2],[4],[31],[125],[105],[34]
Stirling Engine	0.6 - 30	90 - 93	6 - 25	16 - 40	Demonstration First Systems are already available on market [18],[14],[7],[8],[9],[10],[13],[11],[12],[77],[15]
Thermoelectric Generator	> 0.01 – 0.25	91 - 92	1.3 – 2.5	48	Research & Development First System are already available on market [126],[123],[55],[54]

In the following chapters fact sheets, technology develpoments in the last 10 years, and selected monitoring data from practical or laboratory applications of micro steam engines, micro ORC applications, Stirling engines and thermoelectric generators are presented and discussed.

2.2 Steam engines

2.2.1 Fact sheet

Derived from the well-known power plant technology, the steam power process has been developed also for the smallest power range. Using reciprocating engine as expansion machine allows the meaningfully downsize of the steam process to a micro-CHP appliances with less than 50 kW_e electrical power. Due to the external combustion and heat supply, a steam engine allows the greatest possible flexibility in terms of fuel selection. Therefore a steam engine is particularly excellent suited for the use of (solid) biomass in combined heat and power generation applications. The steam piston engine works on the principle of the displacement engine and the principle of operation is the same as for conventional Rankine cycle where an engine is used instead of the turbine. The working principle based on the use of steam produces electricity through thermal evaporation of pressurized water, steam expansion inside a reciprocating engine and condensation of the exhaust steam (Figure 6).

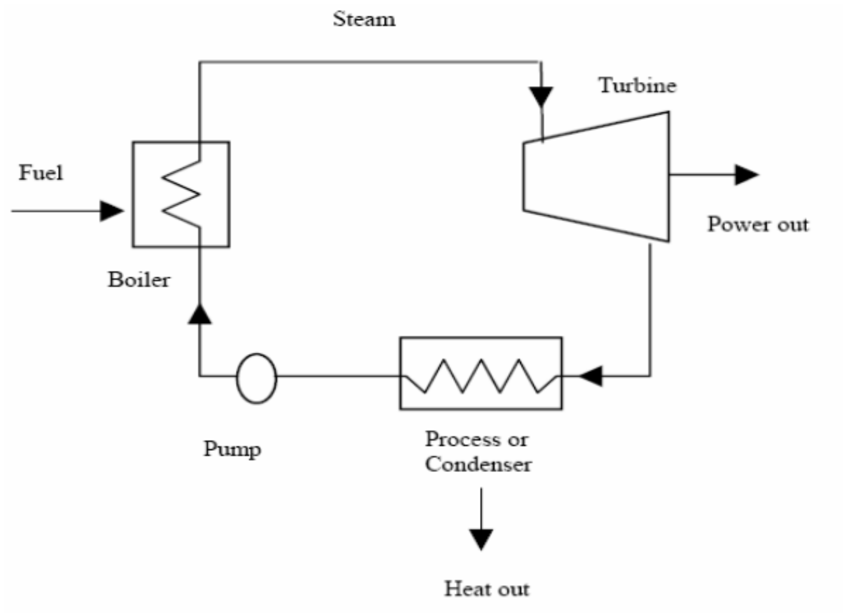


Figure 6: steam process

The operating principle of the steam piston engine is shown in Figure 7. The steam flows into the cylinder until the inlet is stopped by the control piston (picture a). The steam expands and forces the piston down (picture b). In this process, the volume increases and the pressure decreases continuously. After reaching the bottom dead center the piston moves back to the top. The control piston opens the exhaust valve and the exhaust steam flows out of the cylinder (picture c). Then the process starts again [44].

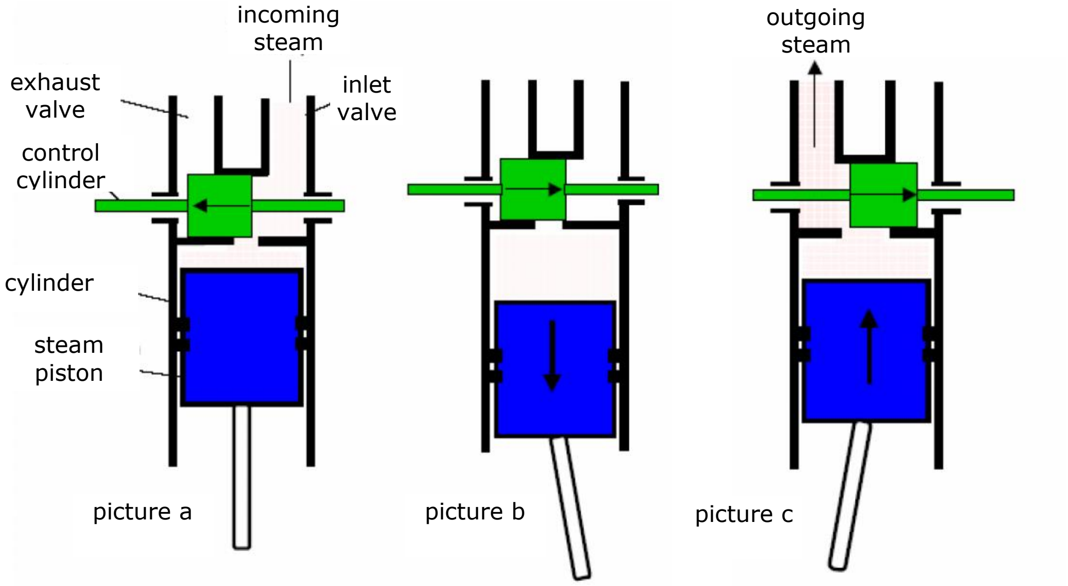


Figure 7: operating principle of the steam piston engine [44]

The mass forces of the reciprocating pistons limit the achievable running speed and performanc. The steam piston engine is a system which is largely insensitive to fluctuating steam conditions (temperature and volume flow) and can be operated with saturated steam. The requirements for the feedwater treatment are relatively low. Fluctuations in steam quality, can be better processed by steam engines than by steam turbines. Furthermore the steam piston process allows satisfactory efficiencies even in partial load operation. Further advantages of the steam piston engine are the robustness, a long life time and the modular design. The modulation capability of steam engines is between 25 % and 100 % without significant loss of efficiency. Steam engines are well proven technologies, with a high level of maturity [3]. The efficiency between steam engine and micro steam turbines in the power range between 1 – 50 kW_e is comparable. The electrical efficiencies described in the literature range from 5 to 20 % [1]; [4]; [41]. In the larger power range, the performance of steam turbines is better because a steam turbine is able to handle a higher level of superheating with a given pressure than a steam engine. Background are technical limitations in the lubrication system of steam engines which complicate the use of advanced steam conditions. Furthermore the steam engine is extremely noisy and requires constant maintenance [1].

2.2.2 Technology developments in the last 10 years

In addition to previous developments of biomass-fired micro steam piston engines (BISON, SteamCell) which were stopped due to insolvencies, there are currently only very few manufacturers. The following are examples of past steam engine developments and current manufacturing companies.

- BISON / Button Energy GmbH

The development of a biomass-fired, steam-powered twin-piston engine of the Austrian company Button Energy GmbH was examined in the period between 2006 to 2013. In 2012 the company Button Energy presented a reference list of 14 appliances in the field. This Micro-CHP technology is an oscillating process steam-driven 2-cylinder 2-stroke steam engine. The special thing about the engine is that it has no rotating parts. The electric power of this system could be modulated between 0.3 kW_e and 2 kW_e. After the second insolvency of the company in June 2013, the development work and market demonstration were stopped [39].

- STEAMCell / ENGINION AG

The core product of this company was a wall mounted Zero Emission Micro Power Unit (Zero Emission MPU). It was a rotary piston steam engine for oil-free operation in the small power range [41]. The heat and electricity output of the rotary piston steam engine was modulating from 2 to 25 kW_{th} and from 0.5 to 6 kW_e. According to Jürgen Freund, Enginion, the expected end user costs of SteamCell were estimated at €1,500.- per kW_e [43]. ENGINION AG field for insolvency in November 2005 [42].

- SPILLINGWERKE GmbH

The currently market available biomass-fired steam piston engines for CHP plants are offered for example by the company SPILLINWERKE from a power range between 100 kW_e – 1,200 kW_e. The Spilling engine is a modular piston expander. It is specially designed for the use in small and medium-sized steam power plants primarily for combined heat and power supply [40]. The focus of these steam engines is mainly on the use of solid biomass, such as wood chips, waste wood or straw. Biomass fired Spilling steam engines achieve electrical efficiencies between 5 % to 11 % within a corresponding load of 50 % to 100 % [41].

In the power range below 100 kW_e, there are only a few research approaches for the use of biomass-fired steam engines, e.g.

- STEAMERGY GmbH & Co.KG / AROSS 3D GmbH

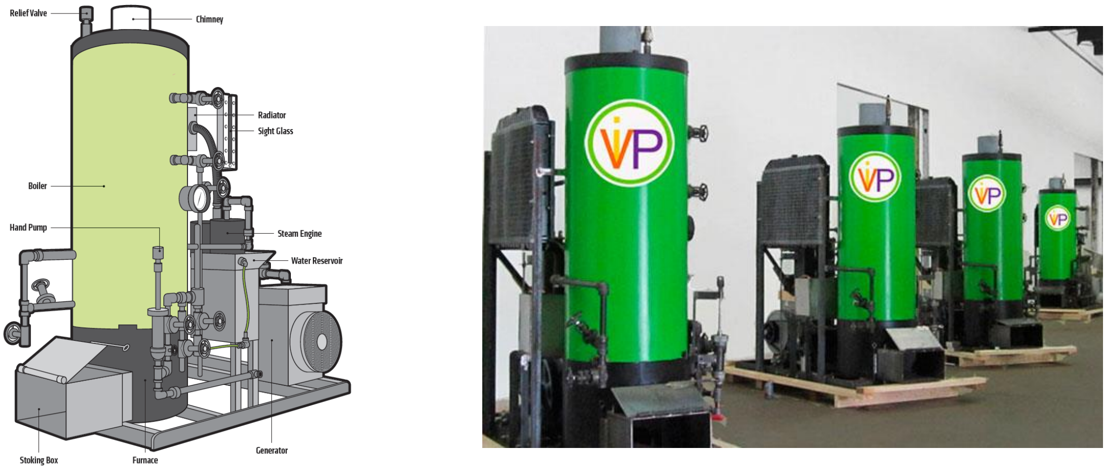
More than five years ago, Aross 3D GmbH began researching and developing a new steam engine technology. From January 2015 to May 2015 the company Aross 3D coordinated the Horizon2020 Project "CHP - Upscaling and commercialization of a highly efficient wood pellets fired steam engine CHP for heat and power generation". The aim of this project was the upscaling and commercialization of a developed CHP system comprising a highly efficient wood pellets fired steam engine. The CHP power output is 50 kW electrical and 175 kW thermal power with 20 % electrical efficiency and 90 % overall efficiency based on wood pellets. The high electrical efficiency is achieved by high steam inlet temperature and pressure of more than 500 °C and 100 bar. The achieved technology readiness level is TRL7 [46]. In March 2018, the developed steam engine chp system, named Steamergy was presented at the fair Energiesparmesse Wels [75].

Table 3 lists the current steam engine developments concerning the development time period, electrical power, overall power, electrical efficiency, investment costs and thermal power.

Table 3: steam engine technology developments

Publication date (last 10 years)	el. power [kW_e]	overall efficiency [%]	el. Efficiency [%]	Investment costs	thermal power [kW_{th}]	tested appliances
Source and additional Information						
2018	20 - 60	~90	~25	~€3,000/kW_e - €3,500/kW_e	60 - 180	n.a.
manufacturer: Steamergy GmbH & Co.KG; [47]						
published in 2010	> 0.3	70 - 95	10 - 15	n.a.	n.a.	n.a.
article: Micro-CHP review: Heizung Lüftung Klimatechnik 1-2/2010 [6]						
2017	10	70	10	$20,000 current production costs	n.a.	n.a.
manufacturer: The VIP 10-kW steam engine [115] VIP's pilot power plants are currently on the ground in East Africa; Market trials of the new units will begin in 2016 in Kenya and Ghana						
2017	30	90	17 - 20	€9.5/W_e	n.a.	n.a.
manufacturer: Green Steam & Neumot; V.E.P. Fördertechnik GmbH; Kalorisches Kleinkraftwerk Neumot; 2017: market ready [116]						

Figure 8 shows some pictures of selected technology developments of different companies.



VIP 10-kW$_e$ Steam engine, ASME [96]

30 kW$_e$ Green Steam [97]

Figure 8: pictures of selected technology developments of different companies

2.2.3 Selected monitoring data

2.2.3.1 Investigations of a rotary piston expander steam engine

Within the R&D project “Bio Power”, subsidized by the Austrian Research Promotion Agency (FFG)

[71], the boiler manufacturer Solarfocus and the Institute of Thermal Engineering of the Graz University of Technology developed a pellet fired micro-CHP for a capacity of up to 10 kW_e and 60 kW_{th} based on a Clausius-Rankine-Cycle (CRC) process and a newly rotary piston expander. The wet steam suitable and oil-free working rotary piston expander was produced by the company EN3 GmbH [50].

Micro-CHP Engine:	rotary piston expander produced by Fa. EN3 GmbH
Boiler:	steam boiler 30 kW_{th} – 60 kW_{th} (Solarfocus)
Fuel:	pellets
Process:	Clausius-Rankine-Cycle; steam engine

Figure 9 shows the mechanical power (coupling performance) as a function of the revolutions per minute at different steam inlet conditions. The maximum power of 4.2 kW was at an inlet steam pressure of 11.9 bar and at 700 rpm. The performance of the steam expander rises with increasing revolutions per minute, increasing inlet steam pressure and/or increasing overheating of the steam temperature [50].

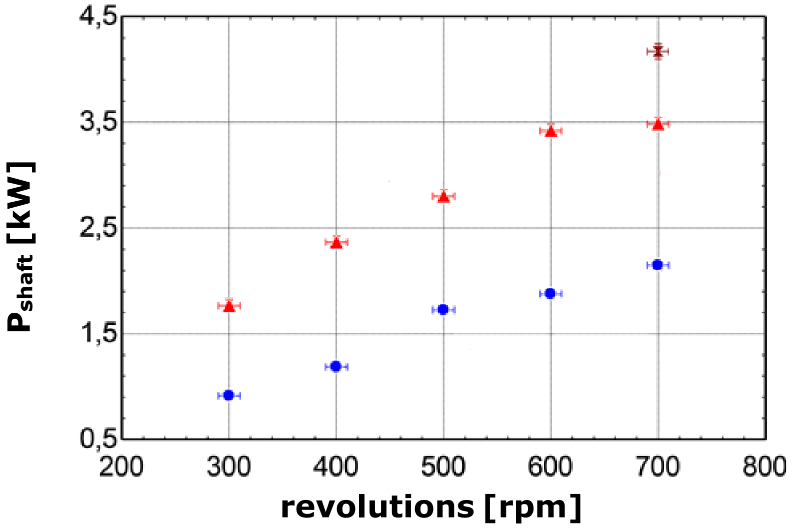


Figure 9: mechanical power (P_{shaft}) versus revolutions per minute at different steam conditions [50]:

- Red triangles:
inlet pressure in the range of 11 bar
inlet temperature in the range of 240 °C
- Blue dots:
inlet pressure in the range of 6 bar
inlet temperature in the range of 190 °C
- Brown symbol:
inlet pressure 11.9 bar
inlet temperature 244 °C

2.2.3.2 Investigations of a 2-cylinder, double cycle steam engine

The steam piston engine BISON was tested in 2009 by the research institution BIOENERGY2020+. This novel steam engine was developed by the companies OTAG and Button Energy GmbH. The possible fuels for this system were natural gas or wood pellets. The working principle of this system was based on the Clausius Rankine cycle. By the combustion of pellets, the boiler produces steam in a pipe-evaporator whereby the steam is expanded, alternating between the left and right operating cylinders. The alternating expansion of steam forces the piston to linearly move back and forth through the armature coil (swinging piston technology) thereby generating electricity. As a result of this expansion, the temperature and pressure of the vapour are decreased and some condensation may occur. The residual heat from the condenser is used for room and water heating. The produced direct current electricity can be used to load batteries for stand alone applications or can be fed into the grid using an AC/DC inverter. The working principle of the system is based on the Clausius Rankine cycle and is shown in Figure 10 [49].

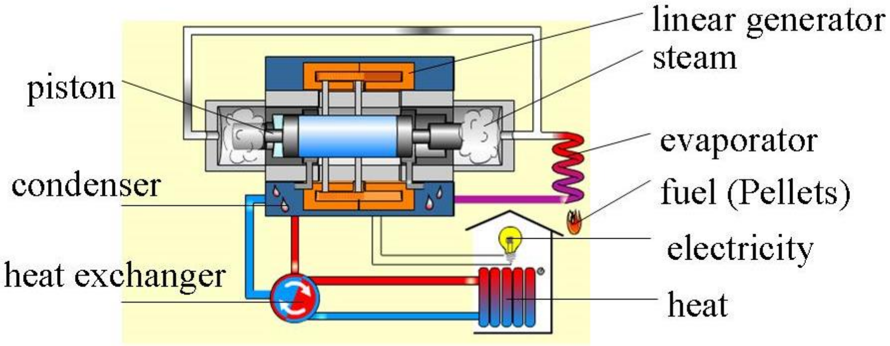


Figure 10: micro-CHP system with steam piston engine [111]

The 2-cylinder, double-cycle steam engine operates without rotating parts. The technical specifications of the steam piston engine are summarised in Table 4 and a picture of the investigated unit is seen in Figure 11 [49].

Table 4: technical specifications of the steam piston engine

Parameter	Value
Nominal fuel heat input	18.5 kW
Fuel heat input range	6 - 18.5 kW
Electrical power output range	0.3 - 2 kW_e
Process steam temperature	350 °C
Process steam pressure	~ 25 to 30 bar
Condenser pressure	0.3 bar
Clausius Rankine efficiency	~ 30 %
Electrical efficiency	10.8 %
Voltage	230 VAC, 50 Hz
Fuel	wood pellets

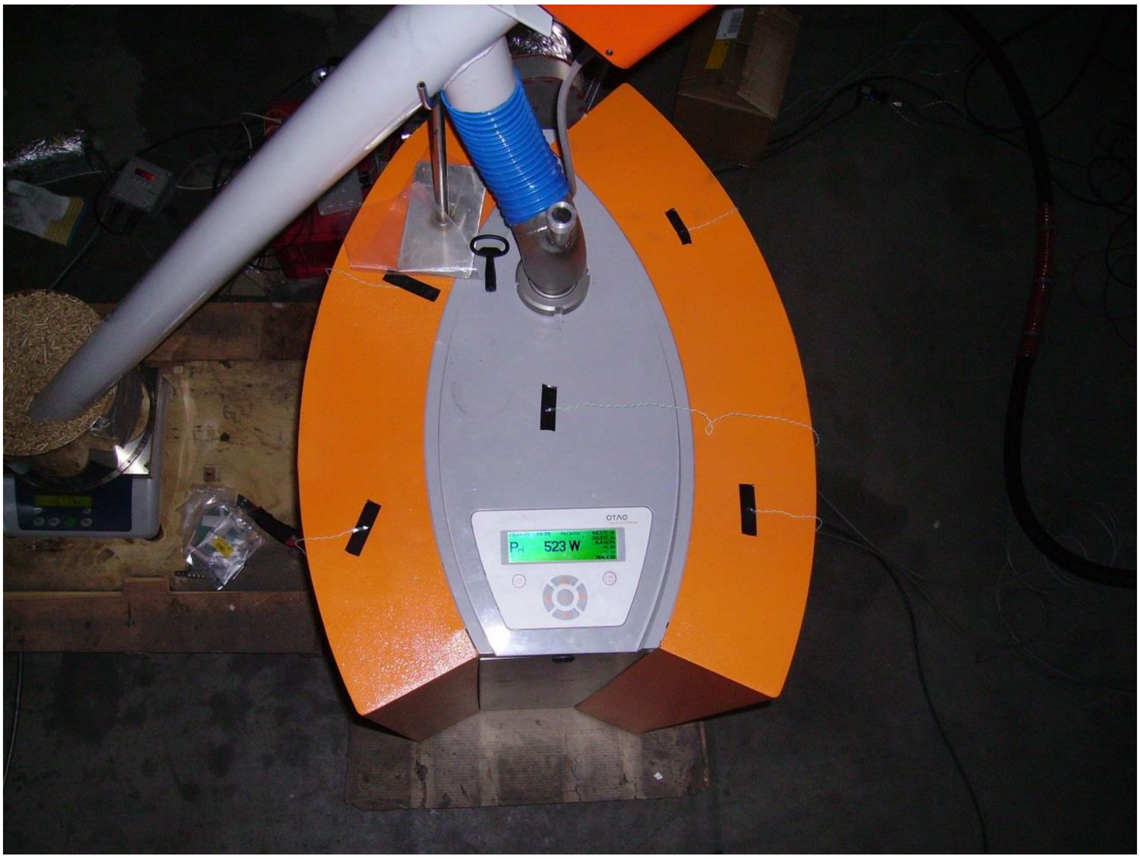


Figure 11: micro-CHP system with steam piston engine [49]

The experimental results for the steam piston engine are presented in Table 5. It was found that an average electrical power of 250 W_e was required to drive all of the auxiliary components for the operation of the micro-CHP system and the water circulation pump. The average power surplus was found to be 1,350 W_e and the measured electrical efficiency was 9.3 % [49].

Table 5: test results for the steam piston engine [49]

parameter	measured results of steam piston engine
Electrical efficiency	9.3 %
Thermal efficiency	85.6 %
Total efficiency	94.9 %
Avg. power production	1,600 W_e
Avg. power consumption	250 W_e
Avg. power surplus	1,350 W_e

2.3 ORC applications

2.3.1 Fact sheet

The organic Rankine cycle is a process which can be compared with the operation principle of the steam power cycle. But instead of water, an organic medium is used as working fluid such as Iso-pentane, Iso-octane, toluene or silicone oil. These fluids are characterized by better vaporization conditions at lower temperatures and pressures compared to water which enables the utilization of low temperature heat sources like solar or biomass applications to produce electricity. To enable the usage of a boiler (heat source) which operates under atmospheric pressure, thermal oil is used for the heat transfer from the boiler to the evaporator. Therefore, no constant boiler supervision is needed [42].

2.3.1.1 Process scheme and explanation

Figure 12 shows the ORC process scheme. As follows the major steps are explained. The heat provision gets done by the illustrated boiler, fed with biomass fuel. The produced energy gets transferred via the heat transfer circuit (e.g. thermal oil) to the evaporator. There the organic working medium in the ORC circuit gets vaporized and subsequently expanded in the circuit integrated turbine, which drives a generator. The remaining energy in the organic working fluid gets recuperated in a regenerator for increasing the electric efficiency. Afterwards the heat gets recovered in a condenser for the usage for district or process heat. Additional the flue gas heat from the boiler also gets a further usage after the heat exchange through an economizer [42].

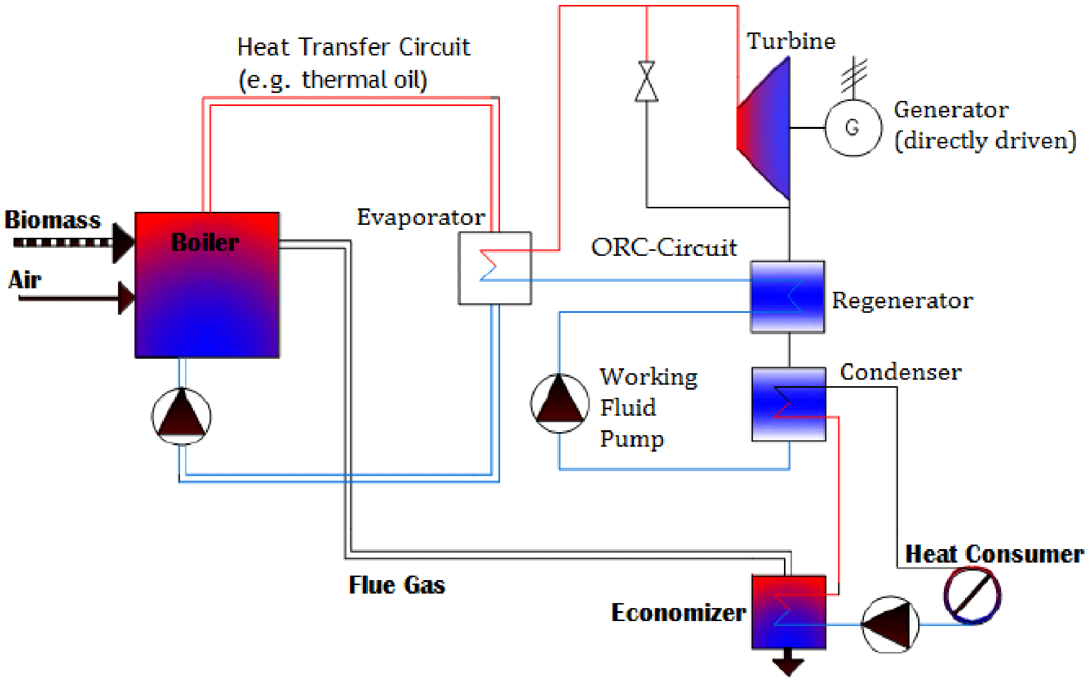


Figure 12: ORC process scheme [73]

2.3.1.2 Heat sources

ORC plants with a high power range have already been used successfully in the geothermal field for decades, where soil heat gets converted into electricity. In the last years the ORC process has been established in waste heat and residual heat utilization whereby for example flue gas heat out of CHP units is utilized to produce electricity. Further sources are solar applications or combustion heat of low-heating value fuels such as biomass [3]. However, the ORC´s are especially suitable for low heat output applications, since process streams within a temperature range of 85 °C up to 500 °C can be utilized [41].

2.3.1.3 Hot water as heat transfer circuit

Already mentioned in chapter 2.3.1.1 the produced energy gets delivered via the heat transfer circuit from the heat source to the evaporator. The circuit is necessary due to avoid overheating and subsequent destruction of the organic working fluid. Instead of thermal oil as heat transfer medium (> 300 °C) also water can be used. Water is the most known heat transfer medium, but temperatures above 100 °C entail a pressurized heat transfer circuit. Several companies already offer appliances with water as transfer medium. For example Bosch KWK Systeme GmbH offers an appliance with a thermal performance of 500 kW_{th} and 90 – 150 °C flow temperature. ORC appliances with power output from 10 to 40 kW_e offered by GILLES Energie- und Umwelttechnik GmbH & CO KG have flow temperatures between 70 – 110 °C and 2 - 6 bar system pressure.

The advantages compared to thermal oil are:

- lower costs
- better environmental capability
- higher performance

The ORC electrical efficiency with the medium water is lower than with thermal oil. But the amount of useable waste heat by a water heat transfer circuit is higher than an ORC appliance with thermal oil.

2.3.1.4 Working fluids

There are numerous organic working fluids available, each having slightly different thermodynamic properties. Hence, the ideal medium for the relevant working conditions and/or heat source can be detected and used. Toluene or n-pentane are used as working fluids for high- temperature ORCs with more than 200 kW_e of power output, whereas hydrocarbons are used as working fluid for low-temperature ORCs, those with less than 200 kW_e of power output [3].

2.3.2 Technology developments in the last 10 years

Depending on local energy resources, the ORC system can cooperate with different types of boilers, geothermic, waste heat and even as a kind of superstructure in bigger energy systems. Numerous research centres worldwide are being involved in the development of such high quality components or entire energy systems. The majority of scientific publications present the studies conducted on research installations under laboratory conditions. In the power range reaching several kW_e (small-scale and mirco-ORC), commercially available solutions have hardly existed up to now [29]. The state of the art are larger scale applications for power production in the industrial sector. Small scale systems have not been economically favourable due to the lack of turbines in that size range with adequate efficiencies (particularly when having to cope with high expansion ratios and variable operating conditions) and high specific costs associated with low initial production quantities. There are four types of small-scale and micro-scale expanders available. It can be distinguished between [33]:

- Scroll expander
- Rotary vane expander
- Micro-scale turbo expanders
- Screw expander

Although different types of expanders may be selected, micro-scale expanders (<10 kW_e) are either not commercially available or very expensive in the form of prototype at present. It is known that screw expander manufacturers for example ORMAT [112], and ELECTRATHERM [113] currently provide commercially screw expanders suitable for ORC-based CHP units with at least 50 kW_e power output, whereas Infinity Turbine [114] provides 10 kW_e modules with a price of $15,000 [33]. A systematic literature review on different types of expanders, mainly units up to 10 kW_e, which are currently under development by industrial and research centres, was presented in the article Qiu et al. [43]. None of the expanders reached series production status. According to Qiu et al. [43], screw and blade expanders have the greatest number of advantages in the power range up to 10 kW_e. The subject matter of the study on different types of expanders is the improvement in efficiency [29].

In Table 6 manufacturers of small- and micro-scale expanders for CHP units are listed.

Table 6 Manufacturers of small and micro scale expanders for CHP units (2011) [33]

Manufacturer Name	Source/ Links	Product type	Expander power	expected Costs
Infinity Turbine LLC USA	[118]	Turbine expander	Model IT10 (10 kW_e)	Turbine only $10,000
ORMAT Tech., Inc. USA	[119]	Screw expander	50 kW_e	n.a.
ELECTRATHERM, USA	[120]	Screw expander	35 kW_e	n.a.
Freepower, UK	[121]	Scroll expander	85 kW_e 100 kW_e 120 kW_e	n.a.

The choices of expanders for ORC-based micro-CHP units within the size range of 1 - 10 kW_e can be summarized as follows [33]:

1. Scroll expanders and vane expanders are likely to be good choices because they can provide high expansion ratios and acceptable performances over a wide range of operations with simple design and low cost. In addition, they are relatively easy to be scaled down in a wide range of 1 - 10 kW_e.

2. The rotary vane expander can represent a good option when the required turbine power output is lower than 2 kW_e [44].

3. If turbo expanders and screw expanders are scaled down to 10 kW_e level, their efficiencies are likely to become unacceptable because they are commonly designed for larger units with high pressure and high temperature operations. Micro-scale turbo expanders and screw expanders (1 - 10 kW_e) are currently under development with the aim of increasing efficiency and reducing costs.

Analyses of the working principles and the characteristics of various expanders have led to the conclusion that scroll expanders and vane expanders are likely to be good choices for ORC-based micro-CHP systems within the capacity range of 1 - 10 KW_e [33].

Efficiencies: The current electrical and total efficiencies at micro-scale ORC appliances are in the range of 7.5 – 13.5 % and 60 – 80 % . For small-scale plants between 7.5 – 23 % and 56 – 90 % and for the large-scale ones up to 15 % and 82 – 89 % [3]. The ORC process can modulate the power output to 20 % of the nominal power while the performance remains satisfying. This is an enormous advantage compared to other evolving micro-CHP technologies like Stirling engines [73].

Economy: Liu et al. [4] state that an ORC turbine is more economical than a steam-driven turbine in terms of capital and maintenance costs due to the use of non-eroding, non-corrosive and low temperature working fluid vapour. But according to the publication EDUCOGEN [39] the organic fluids are more expensive than water and losses of the fluid can represent significant costs. The fluids (e.g. toluene) are also considered hazardous materials. Therefore, safety and materials-handling systems can increase ORC costs. It has been estimated that the average availability of an ORC cycle is 80 – 90 % with a lifetime of 20 years and an electricity production cost of 0.0275 € per kWh [40].

The following Table 7 lists the current ORC developments concerning the development time period, electrical power, overall power, electrical efficiency, investment costs, thermal power and tested appliances.

Table 7: recent micro-ORC technology developments

Publication date (last 10 years)	el. power [kW_e]	overall efficiency [%]	el. efficiency [%]	Investment costs	thermal power [kW_{th}]	tested appliances
Source and additional information						
2018	10	n.a.	~5	n.a.	200	3
manufacturer: GILLES; ENOGIA; 3 reference appliances [121]						
published 2013	> 3	60 - 80	8 - 15	1 – 6 €/W_e	n.a.	n.a.
article: D. Maraver et al. / Applied Energy 102 (2013) 1303–1313; O&M costs: 0,3 – 0,9 €ct/kWh [20]						
2014 - 2017	0.3 - 3.3	n.a.	3.5	n.a.	24 / 9	n.a.
R&D - project: Small-scale BM based CHP Orcan-Energy 93 °C / 35 °C; Fuel: wood chips and wood pellets; amount of heat transferred to the evaporator was about 9 kW_{th} [28].						
2017	4.7 - 30	n.a.	6 - 8	n.a.	n.a.	n.a.
manufacturer: Viking Heat Engines 2017 [124]; CraftEngine CE10 / CE40 100 °C / 20 °C [2]						
2017	8 - 40	n.a.	8 - 11	n.a.	n.a.	n.a.
manufacturer: Viking Heat Engines 2017 [124]; CraftEngine CE10 / CE 40; 200 °C / 20 °C [2]						
2017	16 - 36	n.a.	~6	n.a.	n.a.	n.a.
manufacturer: Viking Heat Engines 2017 [124]; CraftEngine CE 40; 95 °C / 20 °C [2]; TEOPOWER (measured data)						

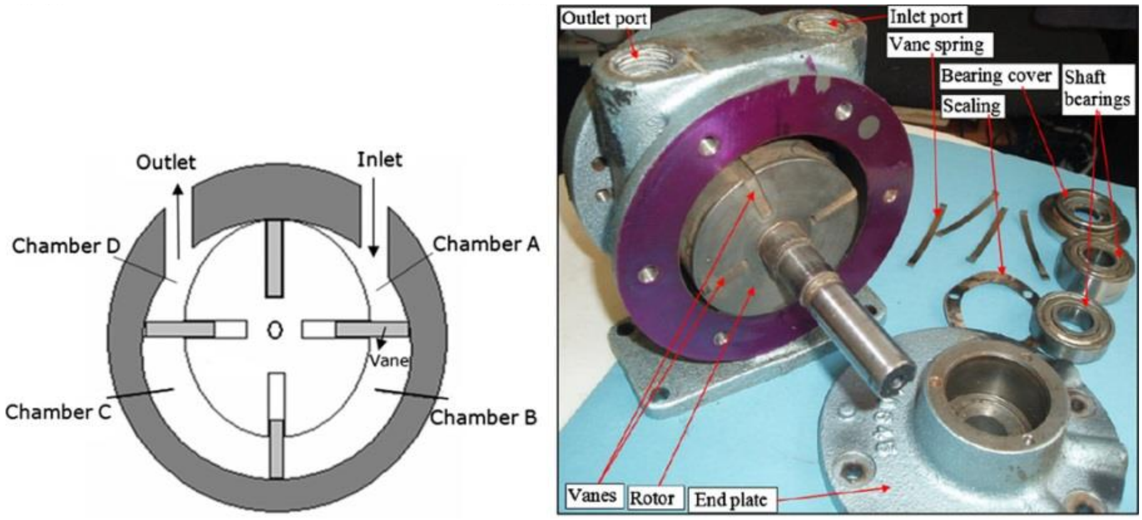
<table>
<tr><th>Publication date
(last 10 years)</th><th>el. power [kW$_e$]</th><th>overall efficiency [%]</th><th>el. efficiency [%]</th><th>Investment costs</th><th>thermal power [kW$_{th}$]</th><th>tested appliances</th></tr>
<tr><th colspan="7">Source and additional information</th></tr>
<tr><td>published 2011</td><td>1.5 – 2.71</td><td>80</td><td>7.5 – 13.5</td><td>n.a.</td><td>n.a.</td><td>n.a.</td></tr>
<tr><td colspan="7">article: Liu H. et al; 2011; UK/Nottingham; A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) – Thermodynamic modelling studies; Biomass and Bioenergy [4].</td></tr>
<tr><td>published 2012</td><td>1.55</td><td>n.a.</td><td>~6</td><td>n.a.</td><td>20 - 30</td><td>n.a.</td></tr>
<tr><td colspan="7">article: ASME ORC 2015, 3rd International Seminar on ORC Power Systems, October 12th – 14th 2015, Brussels, Belgium; four-stage radial microturbine; abs. pressure at turbine inlet 9.2 bar; temperature at turbine inlet:162 °C; abs. pressure behind the turbine: 1.86 bar [31].</td></tr>
<tr><td>published 2017</td><td>50</td><td>n.a.</td><td>n.a.</td><td>n.a.</td><td>550</td><td>n.a.</td></tr>
<tr><td colspan="7">article: Mini Green Power (partner from Enogia)[125]; The Mini Green Plant turns green waste into energy through a gasification process.</td></tr>
<tr><td>published 2017</td><td>10</td><td>n.a.</td><td>5 - 8</td><td>n.a.</td><td>n.a.</td><td>n.a.</td></tr>
<tr><td colspan="7">article: ENOGIA´s ENO-10LT [105]; Low temperature startup: 60 °C; Max temperature: 120 °C; Cooling Water/glycol: 10 to 30 °C</td></tr>
<tr><td>published 2014</td><td>0.5</td><td>83</td><td>5.7</td><td>n.a.</td><td>9.6</td><td>n.a.</td></tr>
<tr><td colspan="7">article: Jradi M. et al 2014; Micro-scale ORC-based combined heat and power system using a novel scroll expander; working fluid: hydrofluoroether (HFE)-7100 fluid; innovative expander modified from an air-conditioning scroll compressor [34].</td></tr>
</table>

In general the challenge of developing micro-ORC technologies is the downscaling which will mainly include the design, construction and installation of the expander for durability testing and experimental validation. As the ratio between the surface and volume of the expander decreases with a smaller frame size, achieving good performance is impeded. In detail the achievement of the necessary pressure level as well as avoiding heat losses cause operating challenges.

Figure 13 shows some pictures of selected technology developments of different companies.

e-pack, Orcan-energy [95]

Craft Engine CE40, Viking Heat Engines and AVL Schrick [93]



Vane-type air motor as an expander [93]

Figure 13: pictures of selected technology developments of different companies

2.3.3 Selected monitoring data

In the scientific article from Jradi et al. [42], a solar-biomass-driven micro-CHP system based on the ORC technology was theoretically and experimentally investigated to provide the thermal and electrical needs for residential applications. The micro-CHP system employed an innovative micro-expander utilizing an environmentally friendly working fluid. In addition, an experimental set-up was built to test micro-scale ORC-CHP system performance under different conditions using hydrofluoroether (HFE)-7100 fluid. The results show the maximum electric power generated by the expander was in the range of 500 W under a pressure differential of ~4.5 bar. The expander isentropic efficiency has exceeded 80 % at its peak operating conditions with no working fluid leakage. The performance under different conditions employing HFE7100 as an environmentally friendly ORC working fluid shows a HFE7100 pressure ratio of 4.6 across the expander. The CHP system has generated a maximum of 500 W of electric power and ~9.6 kW$_e$ of useful heat at the condenser level with an ORC efficiency of 5.7 % and overall CHP efficiency of 83 %. The scroll expander has exhibited a smooth and quiet operation with no working fluid leakage and an isentropic efficiency exceeding 80 % at the peak operating points.

Peterson et al. [15] studied the performance of a regenerative ORC-based system for electricity generation using scroll expander and R-123 as a working fluid with a power output in the range of 187 to 256 W$_e$ and ORC cycle efficiency of 7.2 %. The recorded expander efficiency was in the range of 45 to 50 % with an excessive fluid leakage across the expander during the unit operation.

An experimental testing of a scroll expander modified from a compliant scroll compressor was investigated by Wang et al. [18]. Employing R-134 as ORC working fluid, the maximum reported expander isentropic efficiency attained was ~77 % with 1 kW$_e$ of electric power output.

2.4 Stirling engines

2.4.1 Fact sheet

A Stirling engine totally integrated in a biomass pellet boiler promises to be an efficient and environmentally friendly way to produce heat and electrical power for domestic applications. Whereas natural gas fired Stirling engines are ready to market, solid biomass fired micro-CHP technologies are still under development.

The principle of the Stirling engine is a closed thermodynamic cycle were a pressurized working gas (air, helium or hydrogen) is periodically compressed and expanded to different temperature levels. The working gas expands as it is heated by an external heat source, for example the hot flue gas of a biomass combustion. The expansion of the gas drives the power piston of the Stirling and via connecting rod the rotary shaft of the connected generator. In this way the expansion work of the working gas is transformed to electricity. After the expansion the working gas cools down in a heat exchanger and is compressed by the displacer piston. Then the closed thermodynamic Stirling process starts from the beginning. Figure 14 showhs a scheme of a biomass driven micro-CHP with an alpha-Stirling engine [22].

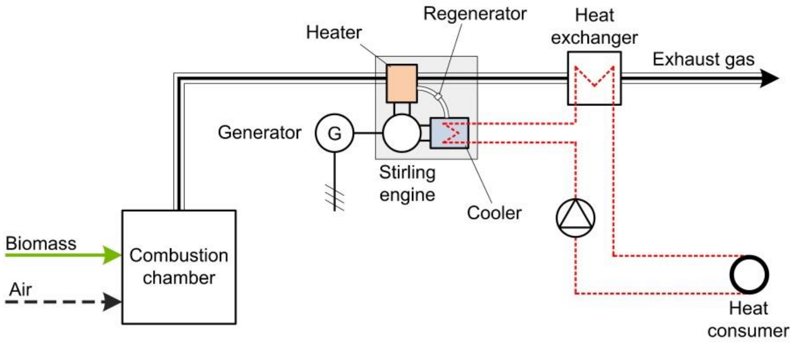


Figure 14: biomass fueled Micro CHP with an alpha-Stirling engine [22]

Stirling engines are externally heated resp. externally fired engines. This fact allows a continuous controlled and atmospheric combustion of fossil fuels as well as renewable energy sources like solid biomass, biogas or landfill gas. Due to the external heat source, it is more easily to control and optimise the combustion process and avoid corrosion and erosion than in an internally combustion engine (ICE). The combustion chamber and flue gases are separated with an heat exchanger to the working fluid of the Stirling process. Hydrogen, helium or air can be used as working fluid in the Stirling process. The thermal resistance and the cleanability of the heat exchanger are essential for the permanent operation of the Stirling engine. Stirling engines are simple in design and compared to internal combustion engines without oil lubrication, ignition system or valves. Compared to the Rankine or Joule cycle process, the thermodynamic process of the Stirling engine is similar to the theoretically optimal Carnot cycle process. Thus Stirling engines have the largest potential for high efficiency. Further technological advantages of the Stirling technology are a low emission level, because of the external combustion, a low vibration and noise level, almost no maintenance and the process can be built as an interchangeable unit [1]. The electrical efficiency of the Stirling process varies between 15 and 35 % and the electrical power output between 0.6 and 50 kW_e [21]. In the fact that Stirling engines are still in the demonstration and commercialization phase the cost of a unit is quite high today, it is around 3,300 – 7,500 € per kW_e.

In the following chapters, some basic information about the best-known Stirling engine developers and manufactures of the last five years is summarized. The described technologies are based on one of the two principal types of Stirling Engine, kinematic or free-piston. The kinematic Stirling engine uses two pistons, which are physically connected by a crank mechanism, whereas the free-piston engine have no physical linkage (no crank shaft or connecting rod) and the displacer oscillates resonantly and the electricity is induced by a linear generator [24].

2.4.1.1 MEC (Microgen)

Originally the linear free piston Microgen Stirling was developed by the BG Group followed by a US design (Sunpower). In 2007 the development of the Microgen unit was taken over by MEC, a consortium of gas boiler companies (Viessmann, Baxi, Vaillant Remeha) and Sunpower. The Microgen unit is a linear free piston Stirling engine. The engines are used in gas boilers as well as in pellet boilers (ÖkoFen). Each of the boiler companies has developed their own variant of microCHP unit [24].

- Nominal electrical output: 1 kW_e
- Thermal output: 3 - 24 kW_{th}
- Application: individual family homes

2.4.1.2 CLEANERGY AB (formerly Solo)

Cleanergy, a Swedish company, was founded in 2008 when they acquired the rights of the V161 Stirling engine from Solo Stirling GmbH. Solo Stirling had started the series production of the model V161 in 2002 and sold around 150 Stirling engines. Now Cleanergy develops Stirling CHP Systems for landfill sites, biogas facilities and waste water plants and also Stirling CSP Systems, which generate power from solar energy. In April 2016, Cleanergy experimented with a Stirling engine fed with methane and low caloric value gases. Currently, the Stirling engines of CLEANERY are installed at more than 100 locations around the world (landfill sites, solar parks,…) [25].

- Electrical output: 2 - 9 kW_e
- Thermal output: 8 - 25 kW_{th}

- Application: commercial CHP, landfill and biogas gas power generation, solar power generation

2.4.1.3 Infinia (formerly known as STC)

The Infinia Stirling was manufactured by Ariston (formerly MTS) and Bosch in Europe as well as Rinnai in Japan. The company Infinia was taken over by Qnergy in 2013 [24].

- Electrical output: 1 kW_e
- Thermal output: 4 - 40 kW_{th}
- Application: individual family homes

2.4.1.4 Qnergy

Qnergy was established in 2009 as a subsidiary of Ricor Cryogenic and Vacuum System (1967). The company Ricor produces annualy thousands of Stirling cyrogenic coolers for the defense and space. In November 2013 Qnergy acquired the US based company Infinia and Qnergy became a sister company of Ricor. The production capacity of Qnergy are up to 18,000 engines annually [82]. Qnergy is offering a 5 kW_e dual-opposed linear free piston stirling engine. The dual configuration of this Stirling should provide a more even power output than single piston configurations, reducing vibration and engine stress.

- Electrical output: 5 kW_e
- Thermal output: ~24 kW_{th}
- Application: commercial

2.4.1.5 Disenco (Inspirit Charger 2.0 and 3.0)

The 3 kW_e Disenco Stirling unit was developed by Sigma Elektroteknisk AS in Norway in 1985, before being taken up by Disenco (UK) in 2003. In 2011 the design was been taken over by Inspirit Energy. Inspirit Energy is formed to complete product commercialisation and certification to GAD and other EU product standards. The website of Inspirit [83] provides an estimated delivery date in 2017.

- Electrical output: 2 kW_e; 3 kW_e
- Thermal output: 10 kW_{th}; 15 kW_{th}
- Application: homes & small commercial

2.4.1.6 Frauscher Thermal Motors

Frauscher Thermal motors (former Frauscher Energietechnik GmbH) was funded in 2014 but the first research and development activities with Stirling engines started already in 2001. The developed and always improved 5 kW_e kinematic-type Stirling module A600 has been in operation for more than 1,000 hours and is already very close to the market entry. In 2016 Frauscher Thermal Motor also started with the development of Stirling modules called fagatec® ENGINES, which combines the alpha and the gamma stirling-type. Fagatec® technology reduces the work of the expansion piston by approximately half compared to the alpha type and by around 30% in comparison to the beta and gamma type. Development status: There are currently engines with 600 ccm of swept volume and a mechanical shaft output of 8 kW imminently to the first field applications in a sewage gas operation. The engines with the type designation fagatec® 600a (with exterior generator) or fagatec® 600i (with generator in the buffer space of the engine) are ready for external use. Frauscher Thermal Motor also focus on the power generation from solid biomass as well as on the development of more powerful engines. [84].

- Electrical output: 5 kW$_e$ and 8 kW$_e$
- Application: commercial CHP, Landfill gas power generation, sewage plant power generation; power generation from solid biomass

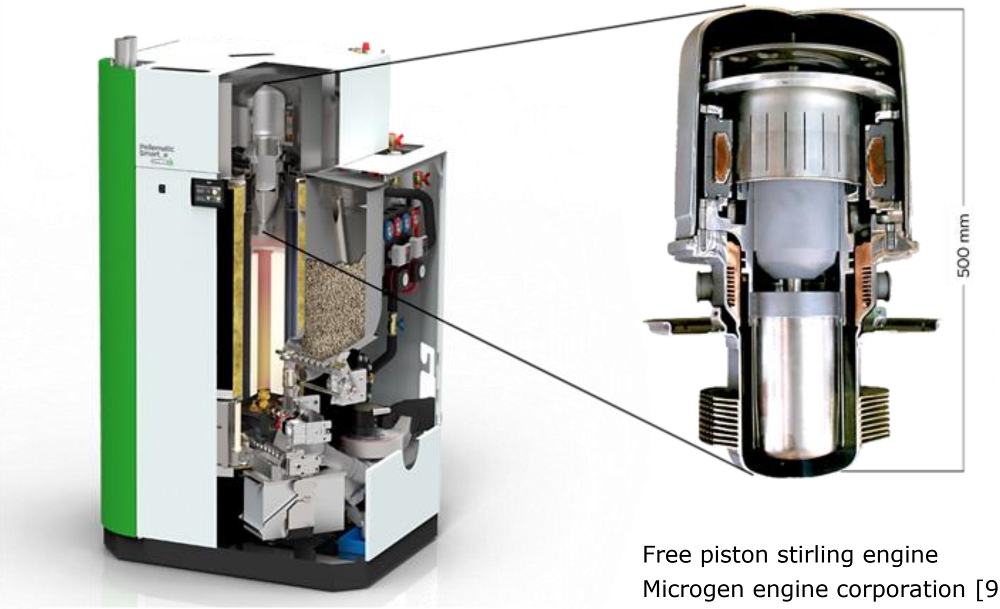
2.4.2 Technology developments in the last 10 years

In fact of different R&D projects in the last 10 years the performance of the investigated Stirling engines was improved significantly and biomass in form of wood pellets or firewood was well tested. Nowadays there are a number of Stirling engines for individual family homes and commercial use available. Nevertheless biomass driven Stirling CHP´s are still in the demonstration and commercialization phase. The following Table 8 lists completed or ongoing R&D-project and current Stirling-developments of manufacturers as well as the key technical data of the latest developments.

Table 8: recent technology developments of Stirling engines

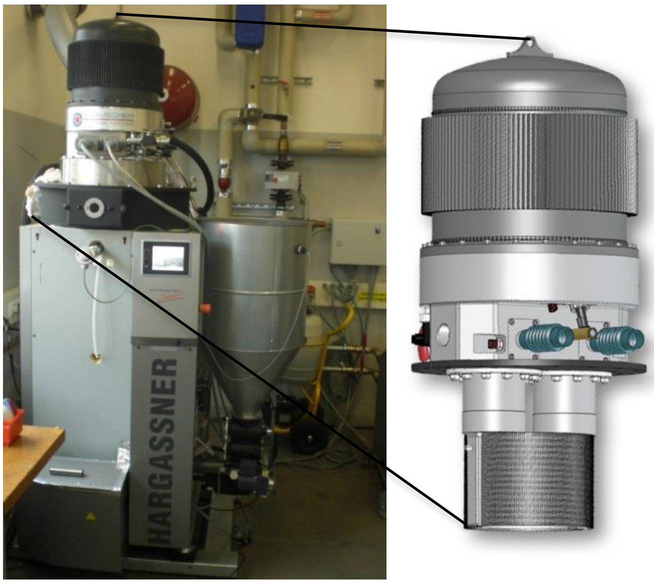
<table>
<tr><th>Publication date
(last 10 years)</th><th>el. power [kW$_e$]</th><th>overall efficiency [%]</th><th>el. Efficiency [%]</th><th>Investment costs</th><th>thermal power [kW$_{th}$]</th><th>tested appliances</th></tr>
<tr><th colspan="7">Source and additional information</th></tr>
<tr><td>2013 – 2016</td><td>5</td><td>>90</td><td>14.4 – 15.5</td><td>n.a.</td><td>25</td><td><10</td></tr>
<tr><td colspan="7">R&D project (FFG): StirBio Stirlingmotor <i>A600;</i> Hargassner Frauscher Thermal Motors; <i>BIOENERGY 2020+;</i> TU Wien [18]; [Figure 15]; [84]</td></tr>
<tr><td>2016 - 2019</td><td>8</td><td>n.a.</td><td>31</td><td>n.a.</td><td>n.a</td><td>2</td></tr>
<tr><td colspan="7">R&D project (FFG): ready-to-connect lean-gas CHP; The still ongoing project has already led to innovations, for example the invention of the fagatech® AlphaGamma® technology with an overall efficiency of 31% (lower heating value fuel to electrical output). [84]</td></tr>
<tr><td>Since 2011</td><td>0.6</td><td>>90</td><td>6</td><td>€24,000.-
(Stirling and boiler incl. VAT)</td><td>9 - 13</td><td>>40</td></tr>
<tr><td colspan="7">Pellematic Smart_e, Company: ÖkoFEN (condensing pellet boiler) and Microgen Engine Cooperation (MEC) (free piston Stirling) Pellematic Smart_e; commercially available in Austria, Germany and Japan [14]; [Figure 15]</td></tr>
<tr><td>Since 2015</td><td>4.5</td><td>93</td><td>7</td><td>n.a.</td><td>40 - 50</td><td>>10</td></tr>
<tr><td colspan="7">Pellematic e-max, Company: ÖkoFEN (pellet boiler) and Qnergy (free piston Stirling: QB-7500) Pellematic e-max [14]; field test in Austria and Germany; [Figure 15]</td></tr>
</table>

2008 - 2011	1	n.a.	20	€4,400.- (Stirling)	45	1
R&D-Project: Company: Biokompakt Heiztechnik GmbH; Gamma Stirling [7]; [8]						
2007 - 2009	3.2	n.a.	23.5	n.a.	50	n.a.
EU Project: "PolySMART" Johanneum Research; wood chips [9]						
2007	30	n.a.	n.a.	n.a.	n.a.	1
Company: Joanneum Research, Thürschweller Energy Systems & Consulting, Schneid Elektronik, Pink: Oko Park Hartberg [10]						
2007	1	n.a.	n.a.	n.a.	15	35
Company: KWB (Pelletfeuerung), StirlingPowerModule Energieumwandlungs-GmbH (SPM) (Stirling) [13]						
2007 - 2012	1	90	9 - 13	n.a.	25	10
Hoval AgroLyt (pellet boiler), Beta-Stirling Dr. Kammerich (D), IZES [11]; [12]; [77]						
2005 – 2010 since 2010 insolvency	1.5 - 3	90	20 - 25	€23,500.- (stirling + boiler)	4.5 – 10.5	400
Company: Sunmachine, (pelletboiler + Stirling engine) [15]						



Free piston stirling engine
Microgen engine corporation [99]

Pellematic smart e [97]



Qnergy Stirling engine [100]

R&D project StirBio 2013 - 2016; Frauscher Thermal Motors, Hargassner; BIOENERGY2020+; TU Wien with 5.0 kW_e Stirlingmodul A600, Frauscher [100]

Figure 15: pictures of selected technology developments of different companies

2.4.3 Selected monitoring data

Marinitsch G. and Kamenik-Lingitz published their article about ´Biomasse-CHP with updraft gasification and Stirling engine` in the conference proceedings of the 12. Holzenergie-Symposium in 2012 at the Federal Institute of Technology ETH Zurich [74]. The investigated Stirling engine was originally planned and designed by Prof. Henrik Carlsen and further developed in the last years. After the first tests with a upcraft gasification and a single stirling engine, the plant was enlarged by 2 and 4 Stirling units. With an fuel input of 210 – 225 kW for a single engine plant, an electrical power of 35 kW_e and a thermal output of about 150 – 160 kW_{th} could be reached. Independent from the plant size an electrical efficiency of 15.5 – 16.5 % and about 50,000 hours of successful operation were demonstrated in various demonstration, pilot and commercial plants. Currently the investment costs of about €10,000.- per kW_e for the investigated Stirling plant system are still very high due to the low quantities and low nominal power. Larger systems, for example a biomass-CHP with 4 Stirling-engines, will reduce the specific investment costs to €6,000.- per kW_e. Also higher quantities will reduce the investment costs. For economic operation, a constant heat consumption of around 150 - 160 kW per Stirling engine and more than 6,000 operation hours per year are required. The investigated Biomass-CHP with updraft gasification and Stirling engine is a very young technology with low quantities and which is still in the market entry phase [26].

The two greatest challenges of a biomass fired Stirling engine are the necessary high flue gas temperatures for efficient operation and the dust load of the flue gases. The main reason of this challenges are that state of the art combustion systems of biomass boilers are not able to produce flue gases on such a high temperature level with low particulate matter. As a result inefficient operation and high maintenance costs of add on Stirling solutions occur. The test results of an integrated, biomass fired Stirling prototype showed furthermore the importance of material selection as the hot flue gases cause immense stress to them [18]. Although some measures to minimize the particle load of the combustion gases were found in this study, there are further potentials for their reduction. For ensuring permanent highly efficient operation, a staged combustion to avoid as much dust as possible and a cleaning concept for the Stirling heat exchanger have to be included. In conclusion, there is still optimisation potential for a biomass fired Stirling micro-CHP system with permanent, low-maintenance, highly efficient and economic operation.

Stirling engines have an enormously high market potential for small and medium-sized enterprises and households. In the long term, the market success of the Stirling technology could be the possibility to use cost-effective renewable biomass-based energy sources for small scale power generation. In comparison to internal combustion engines the advantage of the Stirling engines is the use of any external heat source, for example the hot flue gases of woodpellets, woodchips or logwood combustion. This would not only open up a growing market in wooded countries in Europe and North America, but also in developing and emerging countries. More and more development activities are therefore focused on solid biomass Stirling engines.

2.5 Thermoelectric generators

2.5.1 Fact sheet

Thermoelectric generators (TEGs) allow the direct conversion of heat into electrical power. The TEG receives heat at high temperature and delivers heat at a lower temperature while generating electricity. No working fluids or moving parts are necessary, therefore TEGs operate even soundlessly. Another advantage is a maintenance-free life-long durability. State of the art materials can convert a maximum of 5 - 6 % of the useful heat into electricity, new materials promise 10 % and more [58]. Until now TEGs were only used for certain niche applications especially due to their relatively high price. New applications with higher lot size will result in lower costs [55].

Thermoelectric devices can serve as heat engines, which convert thermal energy directly into electrical energy, or as heat pumps. Depending on the mode of operation, different physical phenomena are utilised. Thermoelectric generation is based on the Seebeck effect, while the Peltier-effect enables thermoelectric refrigeration. These two fundamental principles are material specific effects, and therefore thermoelectric energy conversion works without the detour of mechanical energy.

The Seebeck effect, discovered 1821 by T.J. Seebeck, describes the fact that a temperature gradient along a conductor causes an electric voltage, called thermoelectric voltage. This effect can only be measured or utilised in the setup of a thermocouple, a conductor loop comprised of two dissimilar thermoelectric materials. In case of an open conductor loop, the temperature difference between the two junctions ($T_1 - T_2$) results in an thermoelectric voltage (U_{12}).

$$U_{12} = \alpha_{ab} \cdot (T_1 - T_2)$$

The fact that the thermoelectric voltage depends on the material is embodied within the Seebeck coefficient ($\alpha_{ab} = \alpha_a - \alpha_b$). This is an important material specific property for characterising thermoelectric materials (absolute Seebeck coefficients α_a, α_b) and thermocouples (relative Seebeck coefficient α_{ab}).

Figure 16 shows the open conductor loop comprised of two different thermoelectric materials with the two junctions at different temperature levels together with a schematic sketch of a thermoelectric generator.

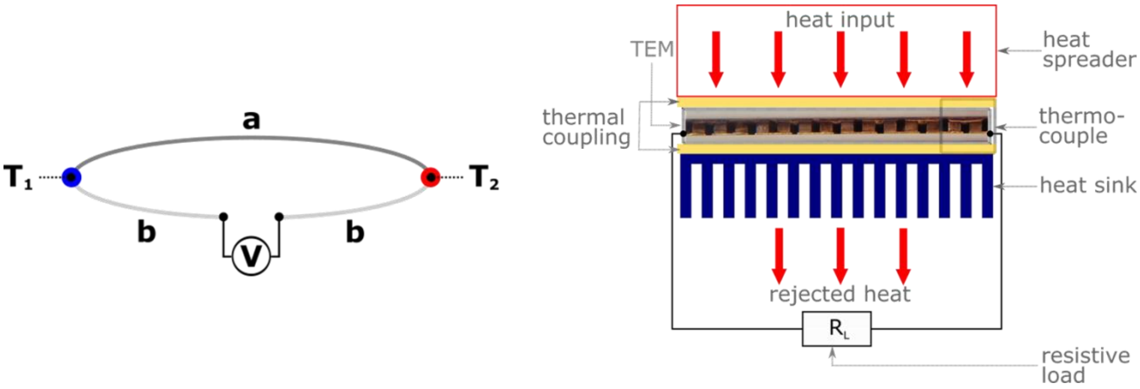


Figure 16: open conductor loop comprised of two different thermoelectric materials (a, b) with the two junctions at different temperature levels (T1, T2) (left), schematic sketch of a thermoelectric generator (TEG) (right)

Reverse conditions demonstrate the Peltier effect, the flow of electric current (I) through the conductor loop, causes a reversible change in the heat content at the junctions. Depending upon the direction of the current flow, heat is absorbed at one and liberated at the other junction [51].

Thermocouples are commonly used as temperature sensors. To utilise thermoelectricity for energy harvesting or electric refrigeration, materials with great Seebeck coefficients, especially highly doped semiconductors, are arranged in thermoelectric modules (TEM). A TEM is comprised of a large number of ingot-shaped n- and p-type semiconductor thermocouples connected electrically in series and thermal in parallel. This setup is sandwiched between electric insulating but thermally well-conducting ceramic plates. In the following the focus is on TEM used for energy harvesting and the combination of TEM with heat spreader and heat sink is called thermoelectric generator (TEG). The difference between applied and dissipated heat equates to the electrical power delivered to the resistive load ($P_{TEG,el}$) [51].

$$P_{TEG,el} = I \cdot \left(\alpha_{TEG} \cdot (T_H - T_K) - I \cdot R_{i,TEG}\right)$$

Among others, important parameters for optimising the electrical power output are the Seebeck coefficient (α_{TEG}), the absolute operating temperatures (T_H, T_K), the effective temperature difference as well as the internal resistance ($R_{i,TEG}$) and the resulting current (I). The power curve of a TEG as a function of the current shows a maximum at the specific current for load resistance equals the internal resistance of the TEG.

$$P_{TEG,el,max} = \left(\frac{\left(\alpha_{TEG} \cdot (T_H - T_K)\right)^2}{4 \cdot R_{i,TEG}}\right)$$

Hence, besides an appropriate choice of thermoelectric devices with respect to the operating temperatures, power adjustment is crucial for optimising the electric power output. The efficiency of a TEG (η_{max}) can be expressed as product of the Carnot efficiency and a reducing factor.

$$\eta_{max} = \frac{T_H - T_K}{T_H} \cdot \frac{\sqrt{1 + Z\overline{T}} - 1}{\sqrt{1 + Z\overline{T}} + \frac{T_K}{T_H}}$$

This reducing factor is dependent on a parameter Z, which is called figure-of-merit, and $\overline{T}$ represents the mean temperature. The greater the figure-of-merit the higher the maximum efficiency. Hence, the figure-of-merit is an important property for classifying thermoelectric devices as well as a single thermoelectric material. The figure-of-merit for a single material is a function of the Seebeck coefficient (α), thermal conductivity (λ) and specific electrical resistivity (ϱ).

$$Z = \frac{\alpha^2}{\lambda \cdot \varrho}$$

Material science is focused on improving thermoelectric materials by maximizing the dimensionless form of the figure-of-merit (ZT), as Z depends on the material temperature T. On lab scale values greater than 2.0 can be achieved, but currently available materials show an average figure-of-merit between 0.5 and 0.8. Furthermore, improving competitiveness of thermoelectric power generation also involves efforts in decreasing costs, developing environmentally friendly materials and especially challenges of employing the thermoelectric materials in devices [51]; [52].

The most common thermoelectric material categories are chalcogenides (e.g. Bismuth Telluride and Lead Telluride) Clathrates, Skutterudites, Half-Heusler and Silicides [53].

Material properties and therefore the performance of thermoelectric devices highly depend on the temperature application range. Hence, established thermoelectric materials are classified in three temperature ranges [51]:

- low temperature materials up to 450 K (Bismuth in combination with Antimony, Tellurium and Selenium)
- intermediate temperature range up to 850 K (Lead Telluride)
- high temperature materials up to 1,300 K (Silicon, Germanium)

In most application fields thermoelectric devices are exposed to inhomogeneous temperature fields (e.g. in a fluid stream), time-dependent thermal fluctuations or thermal cycling, furthermore the temperature of the TEM varies along the length of the thermoelectric legs. Hence, suitable material selection and device design, for example via varying the material, have crucial importance for optimising the performance of a TEG.

Another critical issue concerning fabrication and application of thermoelectric devices are the mechanical properties of the thermoelectric materials, like the coefficient of thermal expansion. The electrical contacts between the thermocouples are mechanically fixed by a solder joint. Hence, high temperature gradients lead to massive thermal stresses on the thermoelectric components. Developing suitable techniques for bonding and thermal coupling are crucial for an optimised and stable operation over the full temperature application range [53].

Different kinds of micro-CHPs are actually under development, but just the production of electricity by thermoelectric generators is perfect for the application in living rooms because there are no moving parts necessary for the electricity production. Hence the electricity is produced absolutely silent [54].

2.5.2 Technology developments in the last 5 years

Currently there are two different ranges of operation temperature for thermoelectric generator: below 250 °C and above 250 °C. For temperatures up to 250 °C TE modules with typical efficiencies of 3 - 4 % are commercially available. To set up a thermoelectric Generator, which should operate in this temperature range, heat exchangers for the hot and cold side of the TE modules, which must be tailored to the particular application, are necessary. The focus of the development in the temperature range up to 250 °C is the representation of adapted systems for optimal waste heat utilization. In the temperature range above 250 °C, no commercial TE modules are currently available. In recent years, rapid progress has been made in the development and field demonstration of high-temperature-capable TEG modules. Highly efficient TE materials have been identified and significant progress has been made in setting up and assembly of high temperature thermoelectric modules [56].

The following Table 9 provides an overview of industrial developers and suppliers of thermoelectric products.

Table 9: companies in the field of material or module development, especially for TEG modules [56]

company	country	TEG-Materials	web
ADV-Engineering	Russia	bismuth telluride Ingots and wafer	adv-engineering.com
Altec	Ukraine	Peltier- and TEG-modules	Ite.cv.ukrtel.net/altec
BASF	Germany	TEG-modules	basf.com
Corning	USA	Skutterudite	corning.com
Gentherm	USA	Pelier-systems; TEG-generators, modules	gentherm.com
Global Thermoelectric	Kanada	Lead-tin-telluride	globalte.com
GMZ Energy	USA	Half-Heusler material	gmzenergy.com
Hi-Z Technology	USA	bismuth telluride	hi-z.com
Komatsu Electronics	Japan	bismuth telluride,	komatsu-

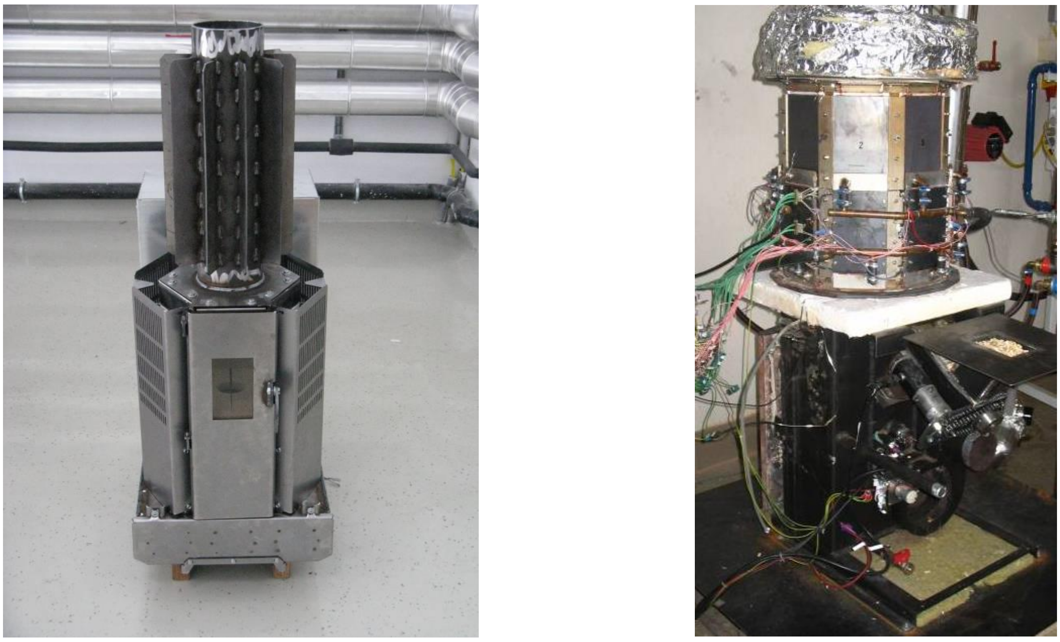
company	country	TEG-Materials	web
		magnesium silicide	electronics.co.jp/english
Marlow Industries	USA	Skutterudite, TEG modules	marlow.com
MicroPelt	Germany	Thin-film modules	micropelt.com
Romny Scientific	USA	magnesium silicide	romny-scientific.com
TEGma AS	Norway	Skutterudite	tegma.no/en.aspx
TEGnology	Denmark	Zinc-antimonide	tegnology.dk
Tellurex	USA	TEG-modules: LASTT + Skutterudite	Tellurex.com
Toshiba	Japan	TEG-modules	toshiba.co.jp/world-wide
Treibacher AG	Austria	Skutterudite	treibacher.com
Evident Technologies	USA	Skutterudite	evidenttech.com

The following Table 10 lists completed or ongoing R&D-projects around biomass-fired thermoelectric generators as well as the key technical data of the latest developments.

Table 10: recent technology developments of biomass fired thermoelectric generators

Publication date (last 10 years)	el. power [$\mathrm{kW_e}$]	overall efficiency [%]	el. Efficiency [%]	Investment costs	thermal power [$\mathrm{kW_{th}}$]	tested appliances
Source and additional Information						
2018	0.25	>92	~1.3 – 2.5	48	10 - 20	n.a.
manufacturer/ type tested product: e-Kaminofen zero with 250 W_{el} manufactured by THERMOELECT (former HE Energy GmbH) [126]; logwood stove; can be ordered from March 2018						
2017	0.01 - 0.05	>91	~1.4 - 2.2	n.a.	n.a.	n.a.
R&D – project: Pellet stove with thermoelectric generator; MiniBioCHP; Project Acronym: ERA-NET Small-scale biomass based CHP [123]; developed by RIKA GmbH and BIOS Bioenergiesysteme GmbH (Project coordinator); project duration: 05/2014 – 04/2017						
2007 - 2009	0.17	n.a.	1.5	n.a.	10	1
R&D – project: BIOTHEG II; BIOmass combustion with THermoElectric Generator; developed prototype: pellet boiler with TEG 250; project coordinator: Bioenergy2020+ GmbH; TEG-generator manufacturer: TEC COM GmbH; performed and funded in the framework of the Kplus-programme; project duration 2007 – 2009; [55]						
2010 - 2012	0.06	n.a.	n.a.	n.a.	3 – 10	1
R&D – project: BIOTHEG III; BIOmass combustion with THermoElectric Generator; developed Micro-CHP prototype: air cooled biomass stove with integrated TEG250HT; [54]						

Figure 17 shows some pictures of selected technology developments of different companies and research institutions working in the field of thermoelectric generators.



Pellet stove with TEG 400 (dummy) [102]

Pellet boiler with TEG 250
fuel input 10 kW_{th}, 170 W_{el} [103]

Figure 17: pictures of two selected technology developments

2.5.3 Measured data of research and development projects

Grid independent pellet boiler with integrated thermoelectric generators: Within the project BIOTHEG II a pellet boiler prototype with integrated thermoelectric generator was developed and first results were presented [55]. The performance of the TEG was observed for different loads and operating conditions in order to realise an optimised micro-scale CHP based on solid biomass. The prototype was designed to reach the theoretically possible electrical efficiency of 2 %. This efficiency can be reached if about 50 % of the available heat streams through the TEG and the efficiency of the TEG is 4 %. This value is lower than the 5 - 6 % compared to state of the art thermoelectric generators due to the operating conditions of the TEG in the system: The hot side temperature cannot be held constant at the allowed maximum of 250 °C because of temperature fluctuations. Overheating would destroy the thermoelectric material has to be avoided strictly. The cold side temperature is higher than best for the TEG in order to reach more than 50 °C in the cooling water of the TEG which will be heating water in commercialised systems [55].

The provided TEG has a nominal power of 200 W. It consists of 16 thermoelectric modules (Figure 18) which are connected electrically in series and are arranged in two rings situated one on top of the other. So the TEG forms an octagonal (almost round) tube which is heated by the flame and hot gas from the inside and cooled from the outside (see Figure 18, right). The thermoelectric modules consist of Bismuth-Telluride which is commercially available and usually used for thermoelectric cooling at ambient temperatures [55].

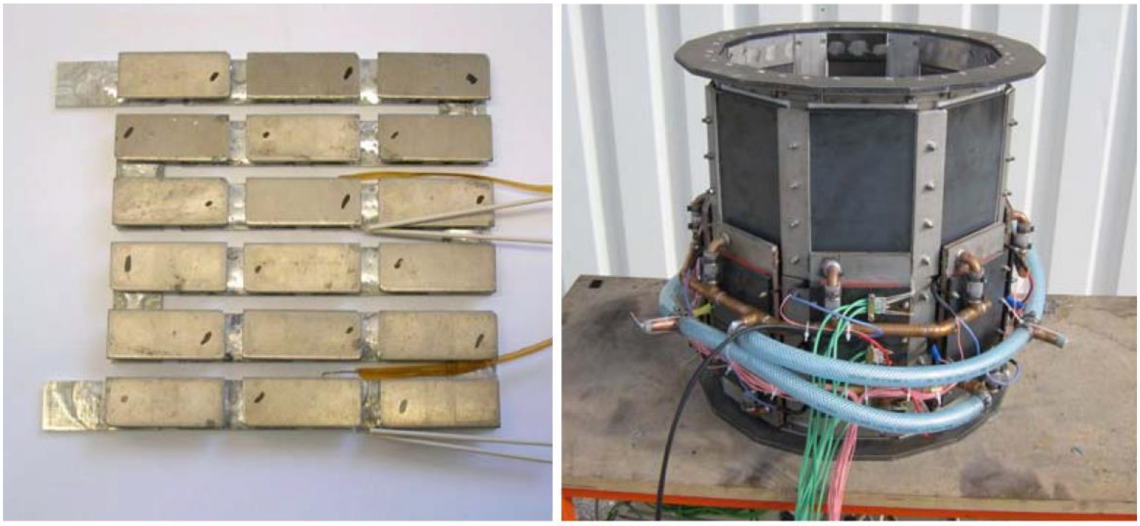


Figure 18: TE-Module and TEG of the prototype [55]

In the first 10 days of operation the prototype was running for almost 50 hours. At steady operation the prototype achieved the values summarised in Table 11.

Figure 19 shows the electrical power output of the system versus the total fuel heat input. Most of the experiments were carried out with about 10kW fuel heat input. The performance varied according to the differences in experimental setup. The higher the fuel heat input, the higher is the electrical output [55].

Table 11: performance of the TEG prototype [55]

parameter	prototype operation	calculated values
electrical power	168 W	200 W
electrical efficiency	1.5 %	2.0 %
efficiency TEG	3.5 %	4 %
heat though TEG	45 %	50 %

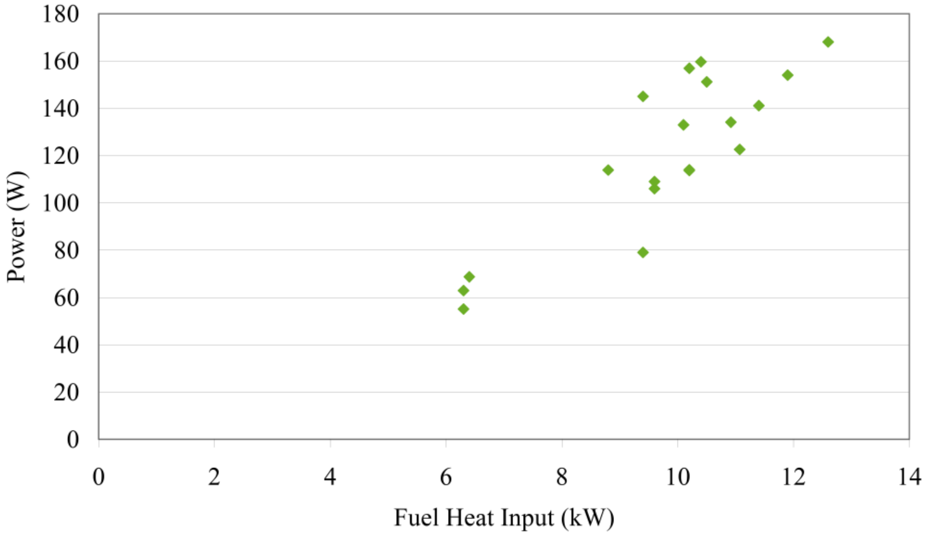


Figure 19: electric power versus fuel heat input of the investigated biomass fired prototype [55]

2.6 Summary and conclusions

Micro-CHP means the simultaneous generation of thermal and electrical energy with a maximum capacity of less than 50 kW_e as defined in Directive 2004/8/EC. Micro-CHP appliances based on internal combustion engines are commercially available technologies operated with biodiesel or biogas. Investment costs of state-of-the-art internal combustion systems are 4 - 6 € per kW_e. Externally fired micro-CHP technologies are not commercially available. Different technological concepts are under development. So are small and micro scale gasification technologies. [35].

So far, the expectations in micro CHP-systems can be summarized in general as follows:

- Contribution to the decarbonisation of the EU economy
- Contribution to decentralized electricity production in smart grids
- Contribution to electrification of the EU energy system

Micro-scale CHP is a highly energy-efficient solution for flexible bio-electricity supply, achieving combined electricity and heat efficiencies of over 85 %. Intelligent control concepts and smart system design allow that even under heat driven operation conditions electricity is mostly generated when actually needed in households. Household peak consumption in the evenings can be reduced and electricity losses in transportation are widely avoided. Direct combustion based micro-scale cogeneration systems are available on the European market. These systems exist for liquid biofuels (diesel engines) and for biogas (gas Otto engines and micro gas turbines). A breakthrough in indirectly fired micro scale cogeneration could lead to a tremendous increase in installed capacity [35].

There will be two distinct fields of application for micro-CHP systems: First, the use as an advanced heating system, which produces electricity in the power range from 0.1 to 5 kW_e and operates 1,500 to 2,000 hours per year (e.g. for single family houses or flats). Second, the use as a local heating plant (e.g. micro-grid) which produces electricity in the range of 5 - 50 kW_e and for more than 4,000 hours per year. The objectives of further R&D efforts in both types of applications are [35]

- to develop and prove integrated concepts (combustion system / heat transfer component / cogeneration technology),
- to develop components,
- to improve component performance (heat exchangers) and component efficiencies (Stirling, thermoelectric materials),
- to improve system efficienciy,
- to optimise control systems (e.g. communication with electrical grid),
- to demonstrate long-term performance to assess reliability and techno-economics of micro CHPs in field operation, and
- to reduce costs.

As an accompanying measure, the development of a testing procedure, preferably implemented into a European standard, for micro-CHPs is required to facilitate market uptake and to provide a point of reference for technology developers as well as for customers. Technologies which may be considered are thermoelectrics [36], Stirling engine, steam cycles, ORC and externally fired hot gas turbines for solid biomass based cogeneration. Biogas and syngas applications may also include micro gas turbine and fuel cell technology. The latter applications require above all substantial research into gas cleaning [35].

Further R&D activities should focus on the following:

- In 2050: No heat production without cogeneration and storage systems [36]
- Costreduction by technical optimization with consideration of serialproduction
- Reduction of maintenance costs
- Development of high temperature- and high corrosion-resistant heat exchanger
- Material development (seals, heat exchanger)
- Integration in smart houses and smart grids
- Development of efficient storage systems (electricity, heat) to avoid grid losses

The electric system efficiencies based on solid state technologies (i.e. thermoelectrics) should reach 2 % by 2020, and for systems based on thermodynamic cycles the electric system efficiency should reach 7 %. As to the different applications, investment costs may vary as well from ~10 € per W for solid state cogeneration to ~3.5 € per W for thermodynamic cycle based technologies [35]. Most of today´s operated CHP-systems < 50 kW_e are heat-driven internal combustion engines fueled with natural gas.First biomass micro CHP-systems (mainly > 10 kW_e) are on the market. Experiemces with tem can be summarized as follows:

- First market ready biomass fueled micro CHP-systems are economical and ecological, if the produced heat can be used.
- Payback periods of 5 years are achieveable.
- First micro-scale CHP technologies fueled with solid biomass are market ready:
    - Steam engine
    - ORC-Process (> 10 kW_e)
    - Stirling engine

There are also lot of ongoing R&D developments (mainly < 10kW_e), e.g. in the fields of

- thermoelectric generators, and
- fuel cells.

It is, however, still not clear, which technologies will be established on the market. There is a long way until full market penetration. Modern CHP-systems are optimised for electricity to substitute peak demand. This tends to electricity-driven systems with higher nominal capacity and lower operating hours.

Small scale CHP ranges from 50 kW_e to 1,000 kW_e.Technologies applicable in this power range are mainly

- steam engines,
- ORC applications with turbine or screw expander,
- thermal gasification with piston engine, and
- anaerobic fermentation with piston engine.

Typical applications are in multiple dwellings or hotels as well as in smaller local heating grids. Future small scale biomass CHP-plants are also driven by biogenous waste and residual materials. To use biogenous waste material already matured technologies for treatment and conditioning, e.g. torrefication, are necessary.

The advantage of small scale CHP systems in comparison with medium- and large scale systems is their higher flexibility concerning power control. Biomass fueled CHP-systems should therefore be mainly connected to smart grids and operate together with wind-, photovoltaic- and hydropower plants. Under certain circumstances, small scale CHP plants can also be connected resp. controlled together in a so called "virtual power plant" to contribute to the voltage stabilisation resp. to the reactive power management in the electrical grid [129].

3 Best practice reports on small scale CHP plants with twin screw steam expander technology

3.1 General information

One of the options to realize biomass fired small scale cogenerations systems is the production of steam, which is used in a screw expander machine. CHP plants, based on this technology, are offered in the power range between 70 kW_e and 700 kW_e among others by company Heliex Power ltd. with its head office in East Kilbride near Glasgow [104].

In the following, some details of the CHP plants screw steam expander turbines used by Heliex Power will be presented, together with 6 best practise examples of application of this technology with different biomass fuels.

At this place, we would like to express our thanks to company Heliex Power for the kind provision of information and data and for the cooperation in preparing the subject best practise report.

3.2 Screw expander technology

3.2.1 Thermodynamic cycle

Screw expander technology is in general well established and has been used in air compressors already for a long time [59]; [60]. The technology however is also suitable for expansion of different working fluids in a thermodynamic cycle. The advantages in comparison with a steam or gas turbine are in principle:

- Technology is basically simpler than turbine technology.
- Components are more robust.
- System contains fewer parts.
- Lower speeds and forces.
- Accepts fluctuating mass flow rates and pressure.
- Not sensitive to steam quality.
- No risk of damaging by wet steam.
- To be manufactured relatively cheaply.

The rotors give pure rolling contact and low contact forces which results in exceptional efficiency and reliability. The design results in a large cost saving for the expander by elimination of synchronising gears.

One of the most proven options to use biomass for CHP is the use of a biomass fuelled boiler for the production of steam. Steam boilers are state of the art and nowadays suitable also for a wide range of biomass fuels including biological residues. The most important advantage is the fact, that the operation of the biomass furnace can be optimized in terms of efficiency and harmful emission independently of the thermodynamic cycle.

Figure 20 shows the scheme of a steam circuit, using a screw expander.

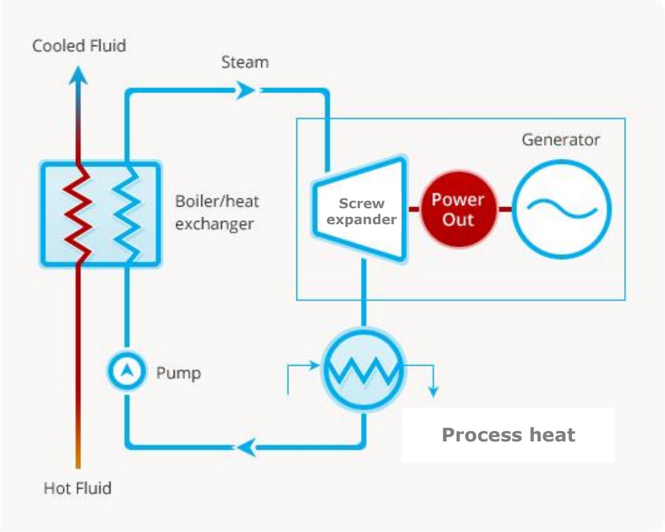


Figure 20: scheme of a steam circuit with screw expander [61]

For application of the screw expander technology for high pressure steam expansion, the components have of course to bbe adapted adequately.

3.2.2 Screw machine design and operation

The main components of a twin screw expander are shown in Figure 21 [61]

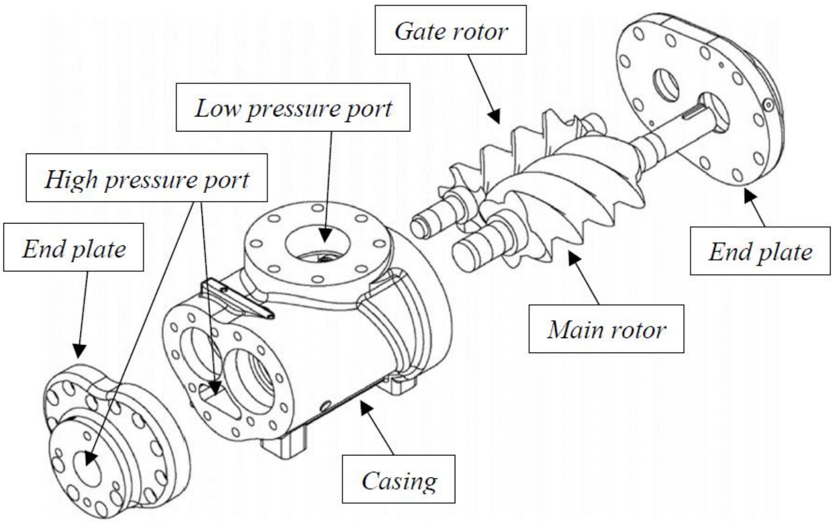
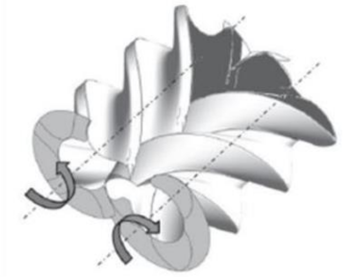
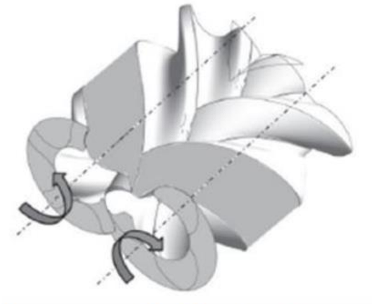


Figure 21: main components of a twin screw expander [61]

Details of the operation of a screw expander are illustrated in Figure 22. Beginning at the top and back of the rotors, there is a starting point for each chamber where the trapped volume is initially zero. As rotation proceeds in the direction of the arrows, the volume of that chamber increases as the line of contact between the rotor with convex lobes, known as the main rotor, and the adjacent lobe of the gate rotor advances along the axis of the rotors towards the front.



High pressure (suction) port closes



Low pressure (discharge) port opens

Figure 22: illustration of the working chamber volume in screw expander operation [61]

At the position where the trailing edge of the working chamber crosses the edge of the high-pressure port, shown in the dark shaded portion of Figure 3.3, the working chamber is closed from the port. On completion of one revolution i.e. 360º by the main rotor, the volume of the chamber is then a maximum and extends in helical form along virtually the entire length of the rotor, shown in the light shaded portion of Figure 22. At this position, the low pressure port starts to be exposed to the working chamber, allowing discharge to begin. Further rotation then leads the trapped volume starts to decrease. On completion of a further 360º of rotation by the main rotor, the trapped volume returns to zero.

For application for high pressure steam expansion, an optimized twin screw expander has been developed by Heliex Power ltd. based on quasi one dimensional analysis of twin-screw machines as described by Stosic and Hanjalic 1997 [62], which has been extensively validated for compressors for a wide range of working fluids and operating conditions. For expanders, the model has been validated for expansion of low dryness fluid (including saturated liquid) using several refrigerants [63]. Using this procedure, machine geometry and rotor profiles have been optimized for a particular set of operating conditions representative of those considered in this paper, and have been fixed for the purposes of the current study. Experimental testing of screw machines optimized for wet steam expansion has been performed [64]. These results have been compared to the results from the computation expander model, and good agreement has been shown between the measured and predicted expander performance. The suitability of the screw expander was shown for generating power from the expansion of wet steam was confirmed in practical operation.

3.3 Innovative screw expander generator set, developed by Heliex Power ltd. (UK)

3.3.1 Concept

An example of a screw expander developed for waste heat and pressure reduction applications are given in Figure 23. As shown, the unit is totally enclosed and contains, within it, the expander coupled directly to a generator. It only requires connection to the steam supply and to the electricity mains. Start up and shut down are fully automated and, in the event of the system failure, the steam supply to the expander is cut off and a parallel pressure reduction valve is activated, thus making the whole industrial process fail safe.

The complete generator set package includes the following components:

- Steam expander
- Electrical generator
- Mechanical power transmission from the expander to the electrical generator
- Inlet steam control valve
- Reverse flow safety bypass and check valve
- Electrical control panel, including controller and sensors
- Base frame, canopy and internal ventilation system

Figure 23: illustration of a process steam screw expander unit (by courtesy of Heliex Power Ltd)

3.3.2 Advantages and disadvantages

The main advantages of the innovative twin screw expander are in general:

- The machine is more flexible in terms of operational conditions - no significant losses in adiabatic efficiency are to be expected when moving from the design operating parameters.
- The rotors give pure rolling contact and low contact forces which results in exceptional efficiency and reliability. The design results in a large cost saving for the expander by elimination of synchronising gears.
- It is capable of working with wet steam rather than superheated, which is much easier and cheaper to generate, especially in small scale applications (1 to 5 MW_{th}).
- It is better scalable and economically attractive also at small scale (below 200 kW).
- The twin screw machines are very robust and can stand significant variation of steam quality (condensate content and chemical dosing) without significant change in performance and reliability. Standard turbines however are more strictly in terms of steam quality, pressure and temperature, which generally means a much more expansive installation and, in case of small scale biomass boilers, smaller ability to handle low quality fuel (e.g. fuel with high moisture content, biological residues).

The main disadvantage of a screw expander in comparison with a standard superheated steam turbine is its overall lower electrical efficiency, which is generally compensated by the much lower cost for the entire plant.

3.3.3 Range of application

The performance of the machine is basically not dependent on the type of fuel used. As already mentioned above, the dimension and operation of the boiler can be optimized in terms of efficiency and emissions independently. Thus, the technology is suitable also for a wide range of biomass fuels including biomass residues, provided the boiler is capable of properly burning it in terms of efficiency and harmful emissions.

In terms of power range, the machine offers substantial advantages in systems where the output is lower than 1 MW_e, or even less. The optimum power range of the expander unit is between 100 and 400 kW_e.

3.3.4 Operational conditions

In a typical installation, the control system ensures that the steam pressure downstream of the expander is maintained within customer-specified limits. A pressure transducer located on the outlet pipe provides the control signal for the inlet valve to ensure the specified outlet pressure is maintained. The parallel pressure control valve may be used for both back-up purposes and to manage fluctuations of steam demand so that, with careful selection, the expander working hours are maximised and the machine works as long as possible at maximum load.

The overall management of the machine is made by a fully automated control system, which may be a proprietary system generally used for generator sets or programmable logic controller system. The generator set control system may be updated and adjusted to suit the customer's requirements or any other special features of the application. Using an asynchronous generator, the speed control is given by the grid frequency, so the machine needs to be connected to a grid to function properly.

Boundary operating conditions for HP145 and HP204 are shown in the following Table 12.

Table 12: working conditions of GenSet models HP145 and HP204 (by courtesy of Heliex Power Ltd)

Working conditions	GenSet models		Units
	HP145	HP204	
Steam inlet pressure	23.5 (PN25 valve)	23.5 (PN25 valve)	bar abs.
Steam inlet temperature	225 (sat)	225 (sat)	°C
Max. steam outlet pressure	12 - 15	12 – 15	bar abs.
Min. steam outlet pressure	1	1	bar abs.
Rotational speed	4,500 – 5,500	4,500 – 5,500	rpm
Steam mass flow rate	up to 6	up to 14	t/h
Max. pressure drop	15 - 18	20 – 23	bar abs.
Max. shaft power	220	680	kW

3.3.5 Results of practical operation

- Efficiency

  The electrical efficiency, defined by the quotient of power output and fuel input, highly depends on the inlet and outlet pressure conditions. The technology is designed to follow thermal demand, rather than maximizing electrical output, so flexibility is seen as more important than efficiency. The output steam pressure can then be significantly higher than atmospheric to suit the downstream thermal requirement. As a consequence, the power output - and with it the electrical efficiency - will significantly decrease in favour of the higher quality heat delivered to the downstream process.

- Emissions

  The screw expander works in a closed steam cycle and has no emissions at all. The emissions of the whole CHP system are dependent on the combustion quality and the flue gas filtration of the biomass combustion plant, which is not the focus of the subject study.

- Dependability

  Due to its relatively simple technical construction, the dependability of the screw expanders itself is very high.

Also the other components of the screw expander generator set, including generator, transmissions system, steam installation, and control system, are state of the art and their dependability is ensured.

In the case studies mentioned in chapter 3.4, till now no incidents in terms of insufficient dependability have happened.

The dependability of the combustion plant resp. the boiler has to be ensured by the boiler manufacturer. It depends of course of the fuel quality resp. on the availability and price of the biomass fuel, suitable for the applied combustion technology.

3.3.6 Economic benefits

- Costs

  Investment costs per kW of the screw expander generator set (Heliex GenSet) are between 800 and 1,800 € per kW, depending on the size of the Heliex GenSet - the smaller, the more expensive.

  The operational costs are about 3 to 4 % of the capital expenditures on a yearly basis. These are figures for the Heliex GenSet only and do not include the service of the complete CHP system where of the boiler, feedstock and the exhaust treatment has to be included of course. In any case, being an application driven by thermal power demand, generally these additional machineries are paid back by the benefit on thermal power rather than the electrical power generation.

- Benefits, payback period

  The Heliex GenSet offers a very simple, robust and cost effective opportunity to generate power out of systems which are built and designed to generate heat with steam as the heat transfer media, which can also be converted to hot water. On a normal application, the extra cost of adding the Heliex GenSet after the biomass boiler pays back in about 3 years. But when it comes to incentivized schemes (e.g. UK or in Italy), then the payback is well below 2 years and sometimes lower than 1 year. More detailed information respecting different boundary conditions is given in the case studies in chapter 3.4.

3.4 Case Studies

3.4.1 CHP plant in Obertrum am See, Austria (132 kW_e)

The end user is an energy contracting company operating several biomass plants in Austria. The HP142-132kW Heliex genset was installed in May 2016 Obertrum am See.

- Industrial application: CHP in combination with district heating 6 MW_{th}
- Fuel: biomass
- Nominal power: 132 kW_e
- Model: HP145-132 kW

- Steam input pressure: 23 bar G
- Steam output pressure: 10 bar G

Beginning in 2014, Heliex's steam expander technology was presented to the management of the customer. They were interested in technologies that would generate electricity alongside the heat from their biomass system as part of an upgrade to their 6 MW biomass district heating plant in the town.

A Heliex GenSet was chosen because it's an ideal solution for a district heating scheme due to its flexibility in operation, particularly at partial load conditions. It delivers a consistent power output, whatever are the demands of the network. The GenSet has a rated power output of 132 kW_{el}. The availability of the installation was high up to now with only very short outages for maintenance. 8.600 operational hours could be reached till now and are to be expected also for the future. Low maintenance costs and a low fuel price of around 30,- € per MWh allows a relatively low-cost production of electricity and guarantees highly economical operation. Payback under the given conditions is expected under 3 years, even without subsidies.

A picture of the Heliex GenSet in Obertrum am See is shown in Figure 24.

Figure 24: Heliex GenSet installation in Obertrum am See (A) (by courtesy of Heliex Power Ltd)

3.4.2 CHP plant in Fondo, Italy (81 kW_e)

A pellet producer in Fondo, Italy, supplies steam to both, the CHP plant and the local district heating network.

- Industrial application: CHP in combination with district heating, 5 MW_{th}
- Fuel: wooden scraps from a saw mill
- Nominal power: 81 kW_e
- Model: HP145-132 kW
- Steam input pressure: 20 bar G
- Steam output pressure: 10 bar G

A pallet producer in the Italian town of Fondo cooperated with local partners to install a biomass district heating scheme. The integration of a Heliex GenSet completed the plant for the production, and created a CHP plant that generates heat and electricity. Heliex's Italian channel partner SON oversaw the complete project.

The aim of the project was to enhance local environmental resources and ensure a sustainable supply chain. A varying heat demand was taken into consideration because it is low during summer months and much higher during winter. This could impact the amount of electricity generated.

Two high pressure steam raising biomass boilers with a total capacity of 5 MW_{th} were installed in a new boiler house. The wooden scraps from the saw mill are used to fuel the boiler and the low cost heat is sold to the local community. The electricity generated by the Heliex GenSet fed into the electricity grid and is eligible for feed-in tariffs for CHP technology under 200 kW. The Heliex GenSet was chosen because it handles fluctuating steam flows and is a good solution for the varying seasonal heat demand.

A picture of the biomass plant in Fondo, Italy, is shown in Figure 25.

Figure 25: CHP plant in Fondo, Italy (by courtesy of Heliex Power Ltd)

3.4.2 CHP plant in Scotland (106 kW_e)

The client owns and operates a district heating scheme that supplies hot water to nearly 200 homes using thermal energy from a 3.5 MW_{th} steam raising biomass boiler fueled by locally sourced wood chip.

- Industrial application: CHP in combination with district heating 3.5 MW_{th} and Whisky distillery
- Fuel: wood chips

- Nominal power: 106 kW_e
- Model: HP145-132 kW
- Steam input pressure: 16.5 bar G
- Steam output pressure: 4 bar G to 1.5 bar G

A Heliex HP145 system utilises the steam raised in the biomass boiler to generate 106 kW_{el} of electricity, which is used to power the boiler plant room and is eligible for financial incentives under the Renewable Obligations Certificate (ROC’s) scheme. Heliex undertook the supply, commissioning and on-site training, while the client oversaw installation. In this instance the client is not applying for the 'Solid biomass CHP systems,' tariff under the Renewable Heat Incentive (RHI) scheme for heat generated from a renewable source because their biomass boiler was commissioned prior to December 2013.

For newer projects, the system would be eligible for the Solid Biomass CHP Systems tariff, guaranteed for 20 years, in many cases offering a return on investment for the Heliex System of less than one year.

3.4.3 CHP plant in the West Midlands, UK (115 kW_e)

The client in the subject case is a UK biomass developer working with an end user, who operates a 28,000 bird poultry farm in the West Midlands.

- Industrial application: poultry
- Fuel: litter
- Nominal power: 115 kW_e
- Model: HP145 - 132 kW
- Steam input pressure: 18 bar g
- Steam output pressure: 1 bar g

As part of a site expansion, upgrading to five chicken sheds, the end user investigated ways to better use their heating system in order to provide optimum conditions for the birds, while also enhancing cost savings and sustainability. They had previously replaced their heating system with a biomass boiler but were interested in a CHP system that would provide both heat and low cost electricity, as well as eligibility for the relevant tariff under the Renewable Heat Incentive (RHI).

The end user selected a Heliex GenSet as opposed to a competing technology for generating power from steam, such as an ORC system, because of the higher residual temperature at the outlet of a GenSet, required for heating the chicken sheds. The burning of chicken litter provides a low cost fuel source for the biomass boiler and efficient disposal of the chicken waste, which brings even more savings. The fuel savings relate to 1,036 tons of carbon dioxide.

The payback of the Heliex GenSet system in the subject case is less than one year.

3.4.4 CHP plant in The Netherlands (160 kW_e)

Client is a large mushroom farm using a 3.5 MW_{th} biomass boiler to supply heat to the greenhouses.

- Industrial application: farming, nursery
- Fuel: wood chips
- Nominal power: 160 kW_e
- Model: HP145
- Steam input pressure: 18 bar g
- Steam output pressure: 1 bar g

The farm previously had a biomass CHP system in operation, although the integrated ORC system failed to deliver the correct power or temperature outputs. The owners investigated alternative technologies that would use the steam in a biomass boiler to generate a low cost and low carbon supply of electricity and provide residual steam at the correct temperature. Temperature is an important factor in this sector because naturally, mushrooms grow mostly in the woods, on moist and humid ground. This climate is replicated in the mushroom sheds.

A steam raising biomass boiler was integrated with a Heliex HP 145 GenSet. The residual heat is used to warm the sheds and sold next door to a strawberry farm. The electricity is available for use on site and eligible for payments from the feed-in-tariff. The farm requires 700,000 kWh annually. Most of the electrical demand will be met by the Heliex GenSet, payback on the system is expected to be less than three years.

3.5 Optimization measures, recommendations

Extensive research activity was performed at City, University of London, to develop the concept of twin screw steam expander. The research team elaborated the theoretical model which then was transferred into a dedicated simulating software. The data calculated by the software were validated thru extensive dyno rig testing at Heliex Power test facility which demonstrated good correlation between prediction and measured data. Those tests demonstrated adiabatic efficiency typically ranging between 55 % and 75 %, based on the operating conditions and the steam quality (dryness fraction).

Design optimization was required to get the expected performance and focused on internal geometries, material and other technical details resulting in optimal power output and good reliability. Table 13 shows an overview of the Heliex steam expander performance measurements obtained with 3 different test runs of 30 mins each in steady state conditions.

Table 13: Heliex steam expander performance measurements obtained with 3 different test runs of 30 mins each in steady state conditions

	Inlet pressure [BarA]	Outlet pressure [BarA]	Inlet Temp. [C]	Outlet Temp. [C]	Steam mass flow [t/h]	Inlet steam dryness fraction [%]	Shaft power [kW]	Adiabatic Efficiency [%]
1	13.7	3.8	194.3	142.9	2.31	90.0	93.9	70.4
2	13.6	3.8	194.0	142.9	2.47	90.0	92.8	65.5
3	13.7	3.8	194.1	142.2	2.49	90.0	93.9	64.6

The operation flexibility (see test method and table below) allowed to take under consideration a number of applications where standard superheated steam turbines can’t operate. The flexibility is meant in both steam quality and operating conditions (steam flow and pressure) which are typical of small scale biomass plant, where saturated steam boilers are used to recover the heat from the furnace.

The following Table 14 shows the Heliex steam expander performance measurements obtained simulating different operating conditions (3 minutes each) on the same test run.

Table 14: Heliex steam expander performance measurements obtained simulating different operating conditions (3 minutes each) on the same test run

	Inlet pressure [BarA]	Outlet pressure [BarA]	Inlet Temp. [C]	Outlet Temp. [C]	Steam mass flow [t/h]	Inlet steam dryness fraction [%]	Shaft power [kW]	Adiabatic Efficiency [%]
1	5.0	1.5	152.8	111.2	1090	80.0	33.4	64.6
2	5.9	1.5	159.0	111.2	1266	80.0	42.5	62.4
3	8.7	1.4	174.4	110.8	1790	80.0	71.0	56.9
4	10.1	1.4	180.7	111.1	2065	80.0	85.2	54.8
5	13.3	1.4	192.7	111.8	2670	80.0	117.5	51.7
6	13.6	3.0	194.0	134.5	2702	80.0	103.0	62.9
7	13.9	3.9	194.9	143.7	2736	80.0	94.6	67.5
8	14.4	6.1	196.5	160.0	2759	80.0	72.5	73.3

In the case of district heating, the thermal load has large variability during the day and between summer and winter season. Only a very flexible power generation system would be suitable for such application and Heliex genset demonstrated to be the ideal solution.

The graph in Figure 26 refers to a district heating application on the Alps. It shows how the power output follows perfectly the variation of the heat demand on the network (typical peaks on daily cycles).

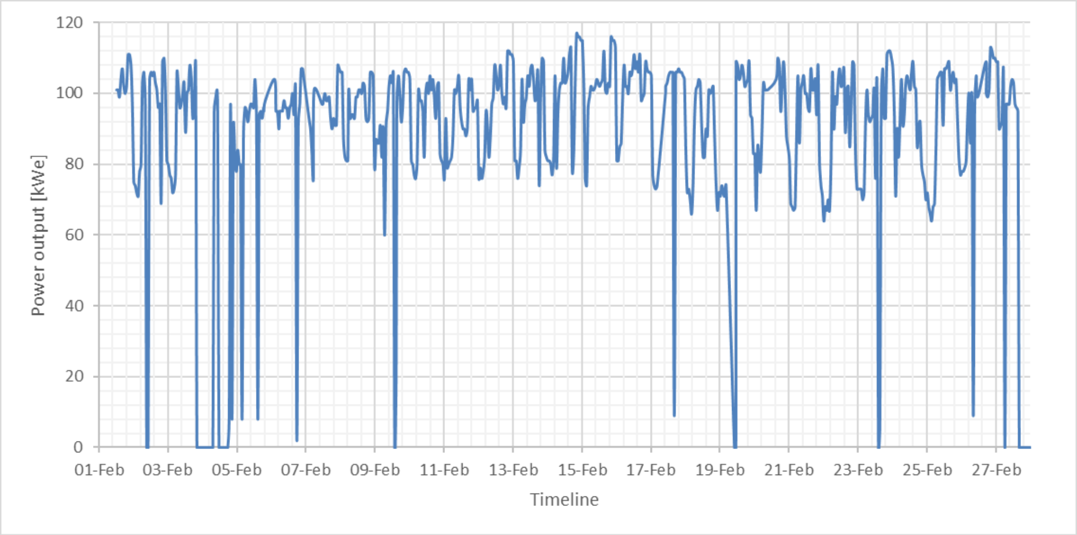


Figure 26: power output of the Heliex genset installed in a district heating network on a typical winter month (February 2018)

The control logic elaborated during the development is based on the measurement of the downstream pressure. In fact, keeping the outlet pressure at constant level by modulating the flow thru an inlet control valve, ensured that the downstream hot water heat exchanger is always fed with the right amount of steam, so the heating network can be supplied with the required heat load. In such conditions, the inlet control valve reduces the operating pressure drop across the expander and, as consequence, the power output is also reduced, as shown in the graph in Figure 27.

Figure 27: correlation between the power output and the pressure difference measured in 3 days of operation at a genset installed at a district heating scheme

Figure 28 shows the power output of the system as a function of the pressure difference in the steam expander, based on the measurement data from Figure 27. The reason for the nearly linear relation in this case is the boundary condition of constant outlet pressure of ~ 0.5 barg. In case of a variable outlet pressure, the relation would not be linear.

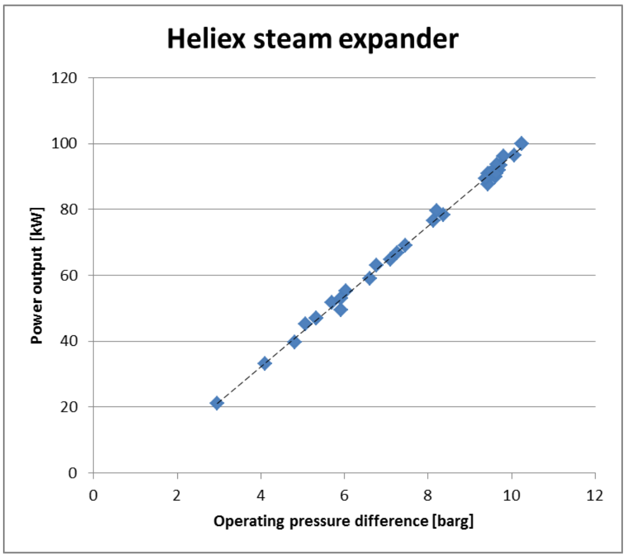


Figure 28: power output of the system as a function of the pressure difference in the steam expander. The reason for the almost linear relation between the power output and the operating pressure difference is the fact, that the outlet pressure was always the same (~ 0.5 barg). In case of variable outlet pressure, the relation would not be linear.

3.6 Summary and conclusions

The Heliex generator set demonstrated to represent a very good solution for generating power on biomass plant where biomass is used as fuel in combustion boilers. The capacity of dealing with saturated or wet steam, the flexibility, the reliability and the low sensitivity to changes in operating represent the main advantage against similar technologies (dynamic turbines or other volumetric expanders). A significant development effort was required to reach the current optimized design and the results were confirmed on both factory test and proper industrial or civil applications.

Beside the technical reliability, the most important indicator for the practical suitability of a technology is in any case the pay back period of the investment. With payback periods in the range bewteen 1 and 3 years, the plants described in the subject chapter can be without doubt seen as “best practice examples” in the field of the different options of CHP production.

4 Best practice reports on micro- and small scale CHP plants with kinetic micro-expanders

4.1 General information

The same thermodynamic approach as presented in chapter 0 can lead to different technological solutions. For instance, other fluids than water can be used to produce steam at lower temperature: The so-called ORC, Organic Rankine Cycles, use refrigerant known for their much lower boiling temperature. Similarly, different approaches exist for expanding this steam (volumetric, kinetic…). One of the enterprises dealing with ORC plants is Enogia SAS, a company based in Marseille [105], which proposes a leading-edge ORC technology for small scale applications (5 kW_e to 200 kW_{el}).

In the following some aspects of the kinetic turbine solution developed by Enogia will be presented and examples of applications with different heat sources will be described.

At this place, we would like to express our thanks to company Enogia SAS for the kind provision of information and data and for the cooperation in preparing the subject best practise report.

4.2 Kinetic turbine technology

4.2.1 Thermodynamic cycle

The thermodynamic cycle on which is based the presented technology, is similar to steam power cycles used in most heat-to-power applications, apart from the working fluid which is an organic one instead of water. Nevertheless, Enogia pushed forth several breakthrough innovations to bring down the power level of the traditional kinetic turbine technology. These improvements led to an extremely compact turbo-expander with a deeply integrated high-speed generator, with a high level of efficiency and reliability. The advantages of the thermodynamic cycles developed are:

- The expansion is continuous in opposition to volumetric expanders, thus no pulsations are created and lower level of vibration can be expected.
- Refrigerants are dry fluids: The risk of dropplets appearance in the turbine is reduced, thus suppressing the risk of damage in case of insufficient heating.
- A large choice of refrigerant fluids can be used, so selection can be based on both their thermodynamic properties and their environmental benignity (e.g. R1234yf, Novec 649)
- These fluids can be used for lubrication of the rotating parts, which limits the maintenance.
- Temperature as low as 70 °C can be used as hot source with the right fluid.

Two facts make the use of such a technology interesting for biomass CHP. Since relatively low temperature can be used, it is a natural choice as a flexible bottoming cycle, as well as higher temperature applications. In addition to that, the use of a dry fluid limits the impact of temperature variations in the boiler which can happen, when dealing with bio-sourced fuel.

Figure 29 shows an example of the application of an ORC module applied to CHP as the main power cycle (Courtesy Enogia SAS).

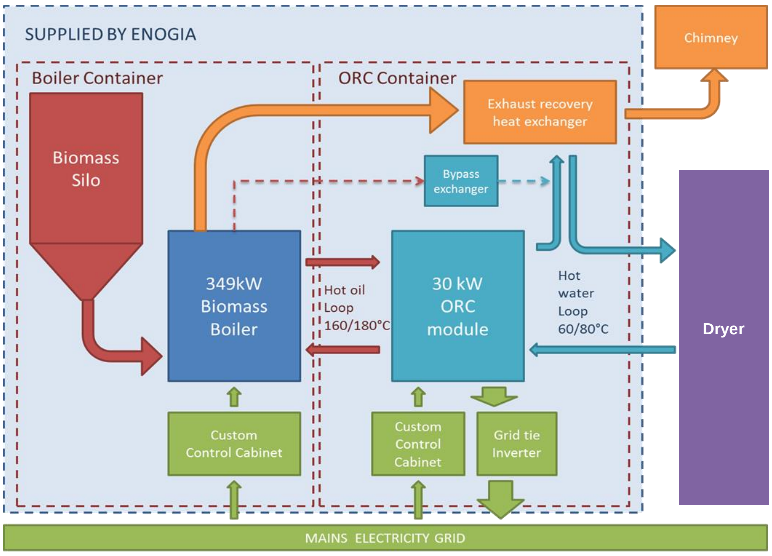


Figure 29: example of application of an ORC module applied to CHP as the main power cycle (Courtesy Enogia SAS)

4.2.2 Micro-turboexpander design and operation

The main components of the micro-turboexpander are shown in Figure 30. The micro-turboexpander is composed of a static axial nozzle that induces an angular component in the fluid flow and drives the turbine. A key characteristic of this type of kinetic turbine is its rotation speed, in the order of magnitude of thousands of rotations per minutes, which allows expanding the fluids in a single stage. To make efficient use of this high speed and further increase the compactness of the solution, a specially developed high-speed generator is directly coupled to the turbine’s shaft. A careful balancing of the whole driving shaft is required to suppress parasitic vibrations.

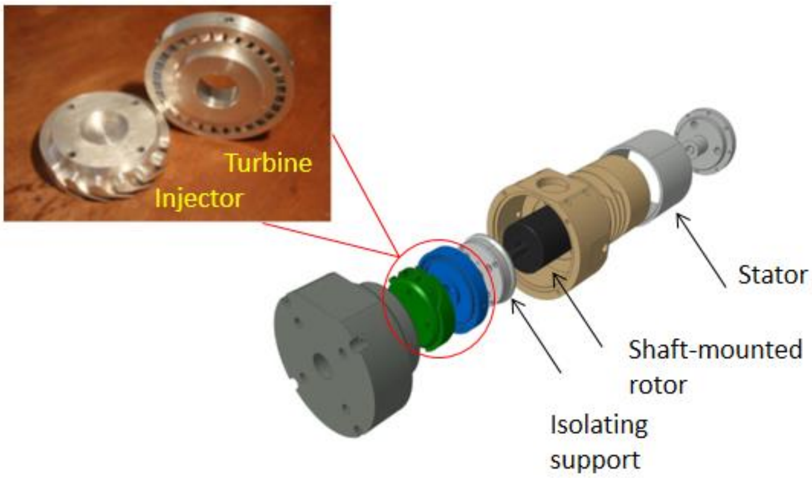


Figure 30: Main components of the kinetic micro-turbine

Figure 31 illustrates the fluid's evolution in the turbine. In the stator, the nozzle blades accelerate tangentially the flow from $\vec{V}_{inj,i}$ to $\vec{V}_{inj,o}$ thus allowing its expansion. The fluid is then deflected by the turbine blade from $\vec{V}_{turb,i}$ to $\vec{V}_{turb,o}$, creating a low pressure zone behind the blade that favours its tangential movement $\vec{V}_{rot}$. As shown in the figure, the axial speed $\vec{V}_{flow}$ of the fluid is constant throughout the whole turbine. This approach of expansion through fluid velocity is opposed to the volumetric approach that comprises screw expanders, scrolls, or pistons.

The pressure drop in the expander, which results in available work on the shaft, depends thus highly on the blade tangential velocity. As a result, single stages are not often considered since a high blade tangential velocity imposes either a high rotational speed that complicates the coupling with the generator (a gear box is required), or a large rotor diameter, both crippling the compactness of the solution. Most industrial turbines applications have a high power output (100 kW at the very minimum) and are multi-staged: stator/rotor pairs are stacked so that the expansion is carried out in successive steps to counter these limitations.

In order to have a more compact design, Enogia has chosen to develop a one staged turbo-microexpander. A careful fluidic design of the stator and rotor for a given pressure drop and fluid couple allows reaching very high rotation speed (over 10,000 rpm) due to a high speed flow in the nozzle. Chocks and vibrations are limited thanks to Enogia's team experience in design and manufacturing of turbo-expanders, and the high-speed electricity generator directly on the shaft prevents from using a high speed gearbox reducer.

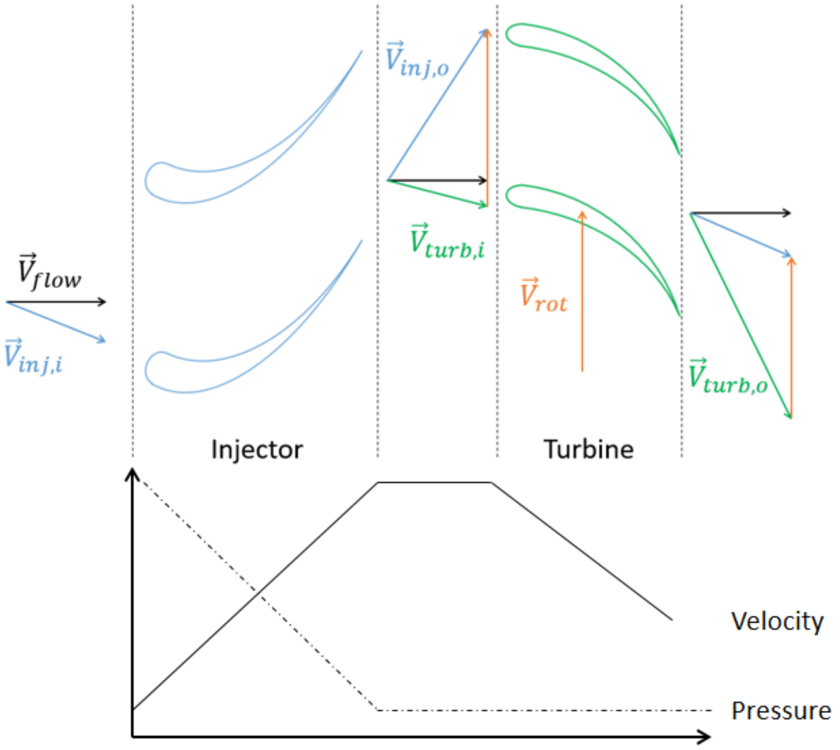


Figure 31: evolution of flow velocity and pressure through a kinetic turbine. *Inj* stands for injector, *turb* for turbine, *rot* for rotation, *i* for inlet and *o* for outlet

4.3 Leading-edge ORC kinetic turbine based generator, developed by Enogia SAS (F)

4.3.1 Concept

Two examples of Enogia's commercial products are shown in Figure 32. Every package is stand-alone: it only requires connections to the hot source in- and outlet, the cold source in- and outlet (i.e. the utility load) and the grid connection. Inside the generator, a pump allows the circulation of the refrigerant fluid. The fluid is vaporized in a perfectly tight heat exchanger on the hot source which prevents the mixing of the organic fluid with the heat transfer fluid (can be oil, water or steam). The produced steam then expands in the turbine, and is condensed in a second heat exchanger on the cold source before passing back through the pump. If the load is partial on the cold source, dry coolers can be integrated to ensure a low enough temperature on the cold source.

Included in the generator are all equipments required to ensure the reliability of the system: cooling and lubrication circuits and pumps for the high-speed generator and inverter, sensors and automation for continuous and safe operations. By controlling finely the refrigerant pump, the flow inside the thermodynamic cycle matches closely the hot and cold sources availability, ensuring optimal working conditions even in degraded operational conditions. Similarly, the speed of rotation is controlled through the inverter to maintain it in the optimal speed range. Cloud-based data logging can be implemented for a live view of operational parameters and produced electricity, and off-site maintenance.

Figure 32: Commercial systems developed by Enogia: on the left, a 10 kW_{el} generator "unboxed", on the right a 40 kW_{el} generator completed

4.3.2 Advantages

The solution, described above has the following advantages:

- High conversion efficiency of the potential fluid energy to the output electricity.

- Low maintenance effort due to very little wear of the moving parts. There are no parts in direct contact – unless the one inside the bearings - giving to the machine a long lifespan. Products are designed to work all year long up to 8,000 hours.
- Lubrication can be done by the working fluid, enabling a simple and cheap design.
- The axial kinetic turbine is considered as compact and lightweight with the highest power to weight ratio. The velocity enables also a smaller generator and electric pack. In addition, the expansion is done inside the nozzle - a static part - making few axial load on the shaft.
- Turbines can be set in parallel to increase the total power.
- Partial injection can be used to adjust precisely and easily the flow rate to the heat source. Thus, a standard turbine can be used in different working conditions with a high efficiency, allowing a large scale production.
- The large variety of refrigerants commercially available provides ample possibility to adapt and optimize the product to any level of temperature, with no or little changes on the turbine design.

4.3.3 Range of application

As stated, Enogia proposes ORC operating efficiently in the range 70 to 500 °C with a liquid or gaseous hot source, producing 5 to 100 kW_e. Further extension of the electrical power outlet range is currently ongoing, with as low as 1 kW_{el} and as high as 400 kW_{el} expected to be commercially available in the medium term.

4.3.4 Operational conditions

The automation system developed for Enogia systems is the key to the efficiency of the system. The best case scenario consists in two perfectly stable hot and cold sources, which allows an optimum efficiency for years. Real case scenario are much less favourable, the actual heat flux extractible or available depending on the load, climate, quality of entrants… By a careful monitoring of the heat flux on both the hot and cold source, the parameters of the ORC cycle are adjusted to optimize its efficiency and/or protecting it. For example if the cold source has difficulty in evacuating heat (i.e. the temperature of the cold source rises), the cycle production is automatically reduced so the condensation does not stop, which would damage the cycle pump. Conversely, if the hot source provides more heat, the pump increases its flow to prevent overheating of the vapour. This can lead to sub or over nominal conditions for the pump and thus reduce its efficiency if such variability of the sources have not been taken into account early in the design.

The second key point in the cycle is the expansion. Its quality is linked to the speed of the turbine, which is linked to electric production. Thus, a strict control of the inverter output is implemented in every product for safe and efficient production.

4.3.5 Results of practical operation

- Efficiency

The heat-to-electricity efficiency in the case of CHP is not the most relevant indicator since it depends heavily on the thermal load on the cold side, as well as on the heat available on the hot side. The emphasis is mostly given to the capability of the solution to meet the thermal load on the cold side with a given hot source availability, the electricity being a by-product of this heat regulation. In this regards, Enogia products have proven their agility and efficiency.

- Environmental impact

The only environmental impact of ORCs comes from the use of refrigerant, which have higher greenhouse potential than CO_2, as well as an impact on the stratospheric ozone. In this regards, Enogia team has shown its capacity in designing and producing tight components and more than meeting European standards in the use and handling of such fluids. Refrigerant used are as environmental benign as possible, with proven uses of innovative fluids with GWP (Global Warming potential) as low as 1 (GWP_{CO2}=1; GWP_{r134a}=1,430).

- Dependability

Enogia has developed a predictive maintenance plan aiming at preventing failure of key components. Since a lot of stress can be imposed to the turbine and bearings when the hot and cold heat flux are out of the contractually set bounds, a remote maintenance and monitoring system was adopted on every products. Alarms are set so technicians are aware of critical changes and if necessary temporarily use manual control of the machine. Vibration sensors are included, preventing early any change in the turbine rotation pattern.

4.3.6 Economic benefits

- Costs

Investment costs per kW of the Enogia ORC are between 2,000 and 4,000 € per kW, depending on its size - the smaller, the more expensive.

The operational costs are lower than 5 % of the capital expenditures on a yearly basis. These are figures for the Enogia ORC only and do not include the service of the complete CHP system where the boiler, feedstock and the exhaust treatment has to be included of course. In any case, being an application driven by thermal power demand, generally these additional machineries are paid back by the benefit on thermal power rather than the electrical power generation.

- Benefits, payback period

Enogia's diversified portfolio of waste heat recovery have proven a payback period of 3 to 8 years without incentives on investment or feed-in prices.

4.4 Case Studies

In the following some of Enogia realisations in the field of biomass CHP are presented. The plant presented in the first example is representative of ongoing projects of various such systems in UK in various states of completion. It is worth noting, that biomass CHP is only a part of Enogia systems uses, the website presents an extensive list of all 50 in-operation and growing Enogia's systems.

4.4.1 CHP plant in Herefordshire, United Kingdom (29 kW_e)

The basic data of the CHP plant in Herefordshire (UK) are as follows:

- Opening: 02/2017
- Design data
    - Industrial application: CHP in combination with house heating
    - Fuel: biomass
    - Nominal power: 29 kW_e
    - Model: ENO40-LT
    - Hot side temperature: 110 °C

The available hot source is a 500 kW hot water stream at 110 °C coming from a biomass installation. The ORC cooling loop is used as a heating source for domestic hot water with an outlet temperature set at 50 °C. The plant is currently being extended, 2 more ORC are coming online this year. Figure 33 shows a picture of the plant.

Figure 33: 40 kW machine, installed after a wood boiler

4.4.2 Biogas CHP plant Foultière, France (8 kW_e)

The basic data of the CHP plant Foultière are as follows:

- Client: GAEC de la Foultière
- Opening: 07/2016
- Design data
  - Industrial application: Wood drying CHP
  - Hot source: Exhaust gas of biogas engine
  - Nominal power: 8 kW_{el}
  - Model: ENO10-LT
  - Temperature of the hot source: 90 °C

Built in 2016, the biogas installation is driven by 80 % of farm wastes – cereal inappropriate for human consumption, herbs, manure – and the last 20 % is coming from flourmill wastes.

The biogas thus generated fuels a 300 hp motor coupled with a 260 kW_e generator. This electricity generated is sold to the French electricity supplier EDF and can cover the needs of 500 people. In addition, an ORC is reusing the installation's waste heat to generate additionnal electricity. The 90 °C exhaust gas animates the ORC while a Dry Cooler is evacuating the heat absorbed by the cooling loop. This warm air blown by the Dry Cooler is directed on logs to dry them making a CHP installation.

Figure 34 shows a picture of the Biogas CHP plant Foultière (F).

Figure 34: Biogas and wood drying installation (La foultière, France)

4.4.3 Biogas CHP plant in Saint Brieuc, France (5 kW_e)

The basic data of the CHP plant in Saint Brieuc (F) are as follows:

- Client: EARL Ker Noë
- Opening: 02/2014
- Design data
  - Industrial application: Wood drying CHP
  - Hot source: Exhaust gas of a 100 kW biogas engine
  - Nominal power: 5 kW_{el}
  - Model: ENO10-LT
  - Temperature of the hot source: 90 °C

Installed in 2014, the plant is powered by the exhaust gas of a 100 kW biogas engine, and produces heat for drying of wood logs. Similar to the previous example in 4.4.3, the plant is the flagship of Enogia's medium temperature / low power solution. The production is steady between 4 - 7 kW_e depending of the biogas and engine production for 4 years now. Such compact solution offers a limited but steady production, ensuring a rapid RoI.

4.5 Optimization measures, recommendations

Since the beginning of Enogia, efforts have been dedicated to capitalize experience and incrementally enhance our products efficiencies. Data logging has been realized onsite for up to 4 years, providing first-hand information on Enogia's systems. Exemplary results are provided below. Figure 35 shows the electricity production and pressure drop in a 5 kW_e turbine for 2 weeks. The pressure drop in the turboexpander is a direct image of the heat power difference on the cold and hot side: A high heat power on the hot side allows a high inlet pressure; a high cold power allows a good liquefaction of the vapours and thus a low outlet pressure. Here it clearly follows the daily exploitation cycle of the biogas power plant, and thus its heat production. This variability was taken into account early in the design and the system prepared accordingly. As a result, the electricity production follows the same trend, going from 3 to 6 kW during a day without issues or fail safe stops.

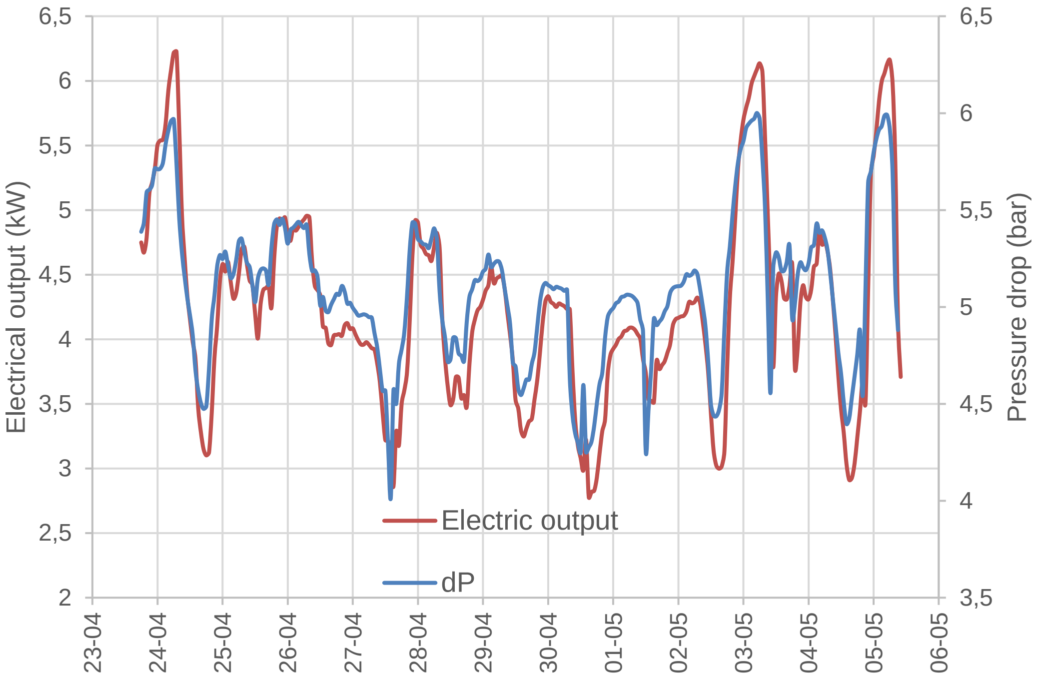


Figure 35: electrical output and pressure drop in the turbine recorded for 2 weeks onsite for a 5 kW$_{el}$ turbine (data from the application, described in chapter 4.4.3)

An other example is displayed in Figure 36 from the best practice example, desrcibed in chapter 4.4.1: on this set of data, the variation of the hot source is much faster (in minutes), but still followed by the electrical output. The electrical output range from 7.5 to 25 kW$_e$. It is a specificity of the system, a low inertia that allows a good reactivity even for the relatively high power of Enogia's range of systems.

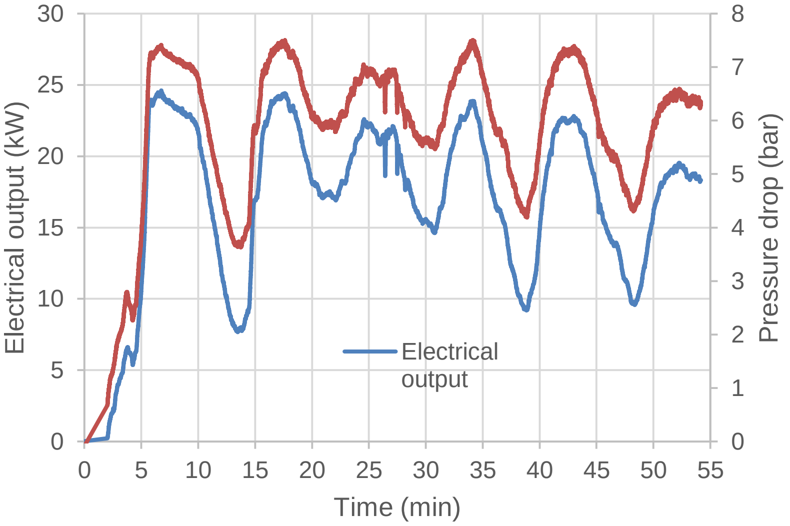


Figure 36: electrical output and pressure drop in the turbine recorded for 1 hour onsite for a 30 kW$_e$ turbine (data from application, described in chapter 4.4.1)

The high flexibility of the system is better shown in Figure 37, obtained by plotting the two sets of data from Figure 36 one against the other. The result is a clear linear trend, the electrical output depending linearly of the pressure drop over a large range. At the same time, the efficiency of the turbine was measured close to 60 % and up to 75 % in the whole pressure drop range. So the system is able to produce efficiently on the whole range, even relatively far from its design point.

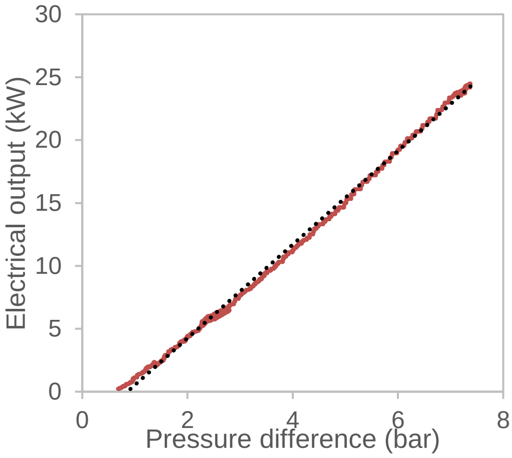


Figure 37: electric output of the system as a function of the pressure drop in the turbine

As a summary, the factor the most impacting the effective adequacy of the solution to the client's needs is a clear definition of the heat reservoirs in terms of temperature levels, power, availability, variability. A lack of power on the cold side can hinder the vapour liquefaction and cause cavitation at the cycle pump inlet. Enogia thus recommend an in-depth study of them, for example based on a measurement campaign onsite or on similar installations. As shown, turbines can be efficient on a large range of working conditions, as long as the heat reservoirs and necessary heat exchangers are well designed.

4.6 Summary and conclusions

The ORC-based turbo-microexpander developed by Enogia is a flexible solution for CHP biomass plants. Heat flux on the hot side can be delivered in liquid or gas phase on a larger temperature range than many other solutions. It can thus be used as the main cycle or as a bottoming cycle, leaving room for overall plant optimization.

Technical reliability of the solution has been proved in several installations in practical operation. The payback period is between 3 and 8 years, which offers a lot of options for environmentally and economically viable CHP.

5 Outlook

5.1 R&D activities and pilot applications in the field of hot air turbines for biomass furnaces, selected examples

5.1.1 Development of a 50 kW_e hot air turbine for application with biomass

Bluebox Energy Ltd, Lee-on-the-Solent (UK) currently develops a 50 kW turbine (MONO HRC) specifically designd for a Solar application as well as a 100 kW DUO system with two 50 kW_e turbines for biomass applications.

A first pilot DUO system for 2 * 50 kW_e is already applied in the frame of an R&D project, carried out by Schmid Energy Solutions in Düdingen (CH), which is described in detail in chapter 5.1.2.

The application of a MONO-HCR system for the EU CAPTure project is in the final stage of build and expected to go into test from October 2018.

Bluebox Energy has now started detailed design of his 50 kW MONO system. It will be based on similar architecture to the DUO+, but employing a smaller turbocharger and single turbogenerator. The first application will be on a Pyrolysis plant with a company called Compag based in Switzerland.

Bluebox Energy also started development of a so called HAT110 system. This system is aimed at developing slightly more power than the DUO+, but with less complexity utilising a different turbocharger to the DUO+ and a single more powerful turbogenerator.

The presently designed 50 kW MONO system will use the same turbogenerator as in the DUO+ systems, but only one instead of two. This will be coupled with a smaller turbocharger to be compatible with smaller biomass furnaces of ~350 kW_{th}.

The main differences between the solutions of Bluebox Energy and more conventional ORC systems are in principal:

- The exhaust heat from our systems remains at a high quality (350 – 450 °C) ideal for hot water and steam production without compromising system efficiency.
- The parasitic losses are substantially lower that ORCs, needing no fluid pumps or condenser fans.
- The hot air turbine needs no thermal oil or refrigerants using just air for the cycle and using oil only for bearing lubrication.
- The efficiency of hot air turbines (~12 %) tends to be lower than ORC's (16 - 20 %) leading to lower electricity production per kW of heat available.

Importantly though, the target cost / kW is well below that offered by ORC's. In the companies experience experience, including the thermal oil heat exchanger and application engineering which is often required, the costs for an ORC is >3500 £/kWe. Whilst the cost for a hot air turbine system is less than £2500 / kW_e (the power module itself is £1500 / kW_e).

5.1.2 Pilot CHP plant in Düdingen (CH), 100 kW$_e$

Schmid Energy Solutions, a swiss manufacturer of boilers for wood logs, wood chips, and wood pellets, with head office in Eschlikon (CH) [106] currently develops a biomass driven CHP plant with a hot air turbine. An R&D project, subsidized fom the swiss Bundesamt für Energie: "Weiterentwicklung und Optimierung einer Heissluftturbine im kleineren Leistunsbereich (80 – 95 kW$_e$)" *("Development and optimization of a Hot air turbine in the small power range (80 – 95 kWe")* was sucessfully completed 2017 [68]. With the hot air turbine, electricity can be generated with wood firing systems with a thermal output in the range of 400 kW and therefore fills the gap in biomass CHP-technology in the smaller power range, which can not be covered by ORC systems or steam turbines [80]; [81].

5.1.2.1 Technology

The hot air turbine HLT-100 Compact (Figure 38) is an automated CHP-station with an electrical capacity of 80 to 105 kW$_e$.

Figure 38: hot air turbine HLT Compact [68]

The waste heat generated during electricity production is used to offer a thermal capacity of 465 kW in form of hot water.

Electricity is generated through an externally fired Brayton process, whereby ambient air is compressed up to 4.1 bar, heated in the hot gas heat exchanger up to 680 °C by the hot flue gases from combustion process and than expanded in the turbine, which drives a generator (Figure 39).

The exhaust air from the turbine, which has still a temperature of some 420 °C, is partly used as combustion air in the furnace, partly to generate hot water.

The hot flue gases from the combustion process are partly recirculated after the hot gas heat exchanger. The remaining flue gases are cooled down in the economiser and cleaned via multi-cyclones and electrostatic precipitators before being discharged via the flue. The further utilisation of turbine exhaust air and flue gases ensures high overall efficiency of the facility.

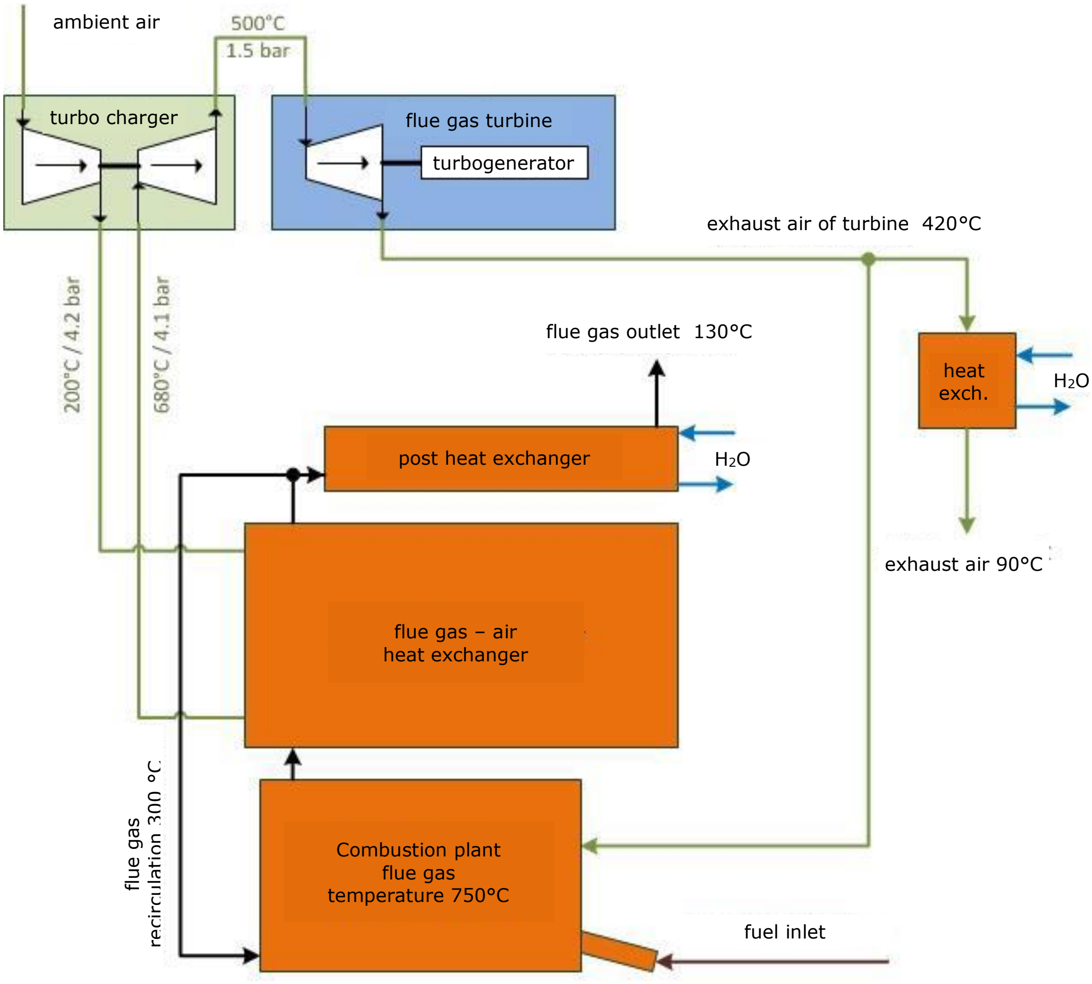


Figure 39: scheme of the process, translated and adapted from [68]

5.1.2.2 Technical data

The technical data of the CHP plant wit hot air turbine, developed in the R&D project are summarized in Table 15.

Table 15: technical data of the CHP plant with hot air turbine HLT-100 Compact

Fuel	untreated wood chips moisture 35 – 55
Combustion chamber	Schmid moving grate UTSR 1200
Turbine	designed for inlet temperature of 500 °C 28,000 rpm
Fule gas cleaning	multi-cyclone and electrostatic precipitator
Thermal capacity	465 kW_{th}
Electridal capacity	80 – 150 kW_e
Own consumption	3 – 18 kW_e
Eledtrical efficiency	13 %
Thermal efficiency	63 % (incl. exhaust air use)
Overall effficiency	76 %
Required space	8 m * 4 m * 4 m

The hot air turbine can by applied in heating systems with a constant thermal output of at least 400 kW and in base load boilers in combination with a peak load boiler.

5.1.2.3 Preliminary experiences with the pilot plant in Düdingen (CH)

In the frame of the R&D project, a pilot plant of a hot air turbine HLT-100 Compact was installed and put into operation in May 2016. Preliminary results confirmed the expected electrical power in the range of 100 kW_e and more under the intended boundary conditions. The power output depends as expected from the turbine inlet temperature and the compressor inlet temperature.

A preliminary evaluation of the operational phase showed the following:

- The goals of the R&D project could be reached.
- The maintanance effort of the hot air turbine is higher than of the furnace itself.
- Practical operation is expected to be economic with a profit of more than 50,000.—SFr/a.

5.2 Optimization of combustion plants in the viewpoint of small scale CHP, ultra low NO_x pilot project of Dall Energy Denmark for Sindal District heating company: 800 kW_e

Autor of chapter 5.2: Jens Dall Bentzen Dall Energy, Hørsholm, Denmark

5.2.1 Introduction

Dall Energy was founded in 2007 by Jens Dall Bentzen, with a seed investment from Spraying Systems, USA. The key product of Dall Energy is the two-stage gasification Furnace.

Dall Energy has received various awards and mentions:

- 2010: Innovation price, Spain
- 2011: European Inventor Award [107]
- 2011: Clean Tech Price [108]
- 2013: Feature in CNN [109]
- 2015: Article in New York Times [110]
- 2017: Blue Tech Award, China

The Dall Energy biomass furnace combines updraft gasification and gas combustion. Combining updraft gasification and gas combustion into one unit offers several advantages to operation and maintenance, emissions reduction, and turndown ratio. These advantages have been verified in 3 heat only plants.

In a next-generation heat- and power plant the design has been modified: A two-stage combustion of the gas, which – according to CFD model calculations – will result in NO_x emissions as low as 100 mg/Nm^3.

Dall Energy has developed a novel biomass two-stage gasification-furnace. The Dall Energy concept combines updraft gasification and gas combustion:

- Gasification of the biomass, which takes place in the bottom of the furnace, is the first stage. Here the solid material is transformed into a combustible gas and fine ash. The gas velocity in this section is very low so the particles remain resulting in very low dust and particle emission from the furnace.
- The gasification gas from the bottom part of the furnace is burnt in the top section during the second stage. The gas combustion itself is in terms of flow, temperatures and emissions, very stable.

Combining updraft gasification and gas combustion into one unit offers several advantages: The plant becomes simpler to operate and maintain, more fuel flexible, the emissions of dust, NO_x and CO are reduced, and the turndown ratio of the furnace can be as high as 10 – 100 %.

The process has been patented by Dall Energy (WO 2010/022741)

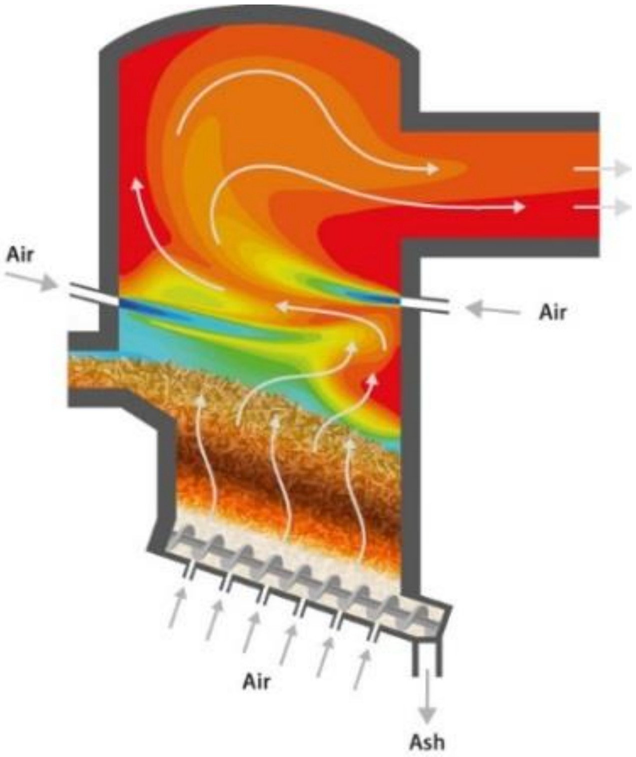


Figure 40: principle diagram of the Dall Energy biomass furnace

5.2.2 Heat only plants in operation

Three plants of the two-stage gasification-furnace type have been built:

- An 8 MW biomass plant in the town of Bogense in 2011 was the first plant. The purpose of the plant was to deliver district heating to Bogense, and to verify low emissions and fuel flexibility. The plant was supported with a grant from the Danish Energy Agency. The emissions was verified in an ETV (Environmental Technical Verification) report.

- The next plant was built in USA, at the factory Warwick Mills in New Hampshire. The plant at Warwick Mills had two purposes:

  - Produce energy (steam) for the factory

  - Destruct VOC (Volatile Organic Compounds) from ventilation air from the factory. The ventilation air from the factory is being used as combustion air in the furnace.

The plant was established in 2013, and put into operation in summer 2014.

Figure 41: Warwick Mills photo: Plant operator Marcel Alex, (left) and Managing director Charlie Howland (right), June 2015

- The third plant was built in Sønderborg, Denmark. It is a 9 MW heat only plant. The plant was put into operation in 2014. Sønderborg has large scale solar heating, so the ambition with the biomass plant was to be able to operate between 10 - 100 % of full load operation with low emissions.

Figure 42: 9 MW Dall Energy plant in Sønderborg

5.2.3 Emissions and performance of the two stage furnace

A summary of results achieved in the three plants can be seen in Table 16 and Figure 43.

Table 16: Summary of results achieved

Operation	Unmanned
Dust directly out of the furnace	30 mg/Nm^3
Dust in the chimney	10 mg/Nm^3
CO	0 mg/Nm^3
NO_x	150 mg/Nm^3
O_2	4 % (dry)
Moisture content in the fuel	20 - 60 %
Fuels	Wood chips, garden waste, spent grain, willow
Carbon in the ash	< 0,5 %
Load	10 - 100 %
Temperature out of the furnace	(+/- 10 °C)
Efficiency	115 % (LHV)
VOC destruction efficiency	99.87 % - 99.98 %

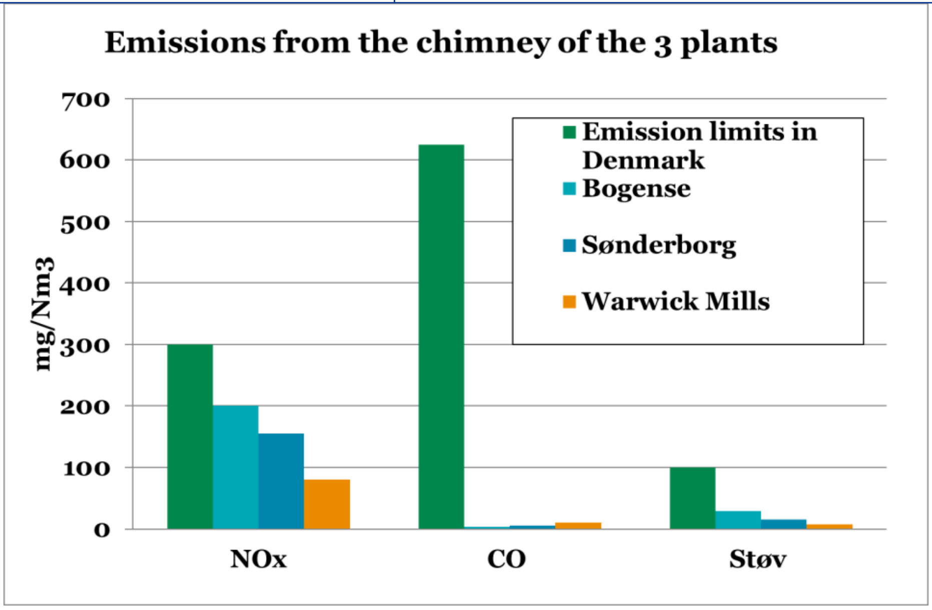


Figure 43: Emissions of the furnaces Bogense, Sønderborg, and Warwick Mills

5.2.4 NO_x reduction with stage divided combustion

In Figure 43 it is seen that NO_x is lower in the Warwick and Sønderborg plants compared to the Bogense plant. The main difference was that the Warwick and Sønderborg plants had two-stage combustion of the gas.

It is well know from literature, that stage divided gas combustion can result in low NOx. With the plants in Warwick and Sønderborg, Dall Energy got some experience with lowering NOx this way.

5.2.5 CHP plant with ultra low NO_x emissions in Sindal

In 2016 a study of a new CHP plant for Sindal was made.

To obtain a high feedin-tarif, the Danish government require NO_x emissions of 100 mg/m^3 or below.

Together with FORCE technology (CFD) Dall Energy investigated, if such low NO_x emissions could be achieved by stage dividing the gas combustion further.

According to the CFD model of Force it seamed like such low NO_x can be achieved without SNCR (Injection of urea or ammonia): When part of the gas is partially oxidized at 900 °C and having a retention time of about 1 second, then the total NO_x will be below 100 mg/Nm^3.

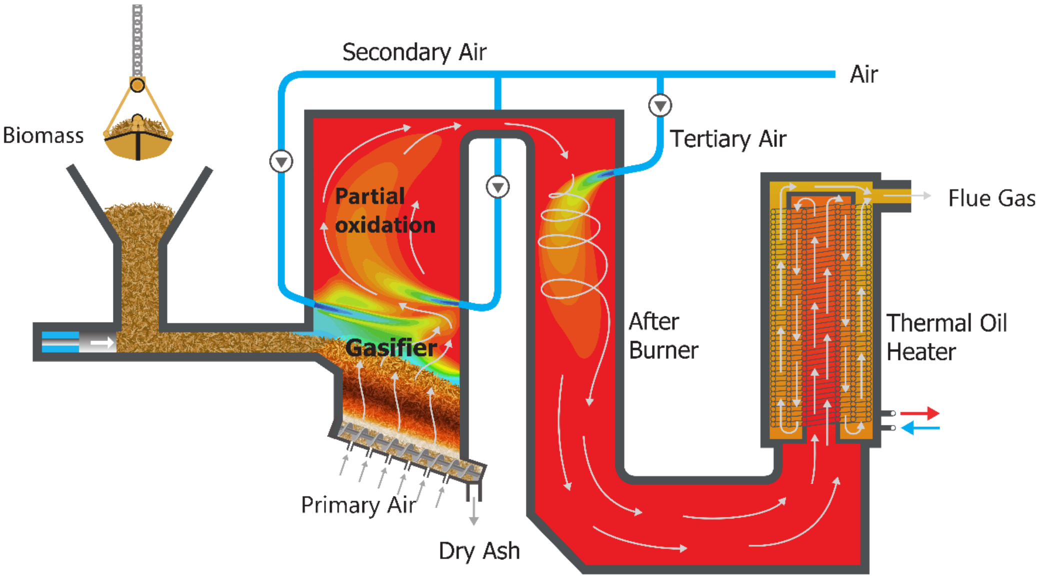


Figure 44: Principle diagram of the Sindal plant. Gas from the gasifier is partially oxidized above the gasifier and finally burned in a separate chamber (Patent pending)

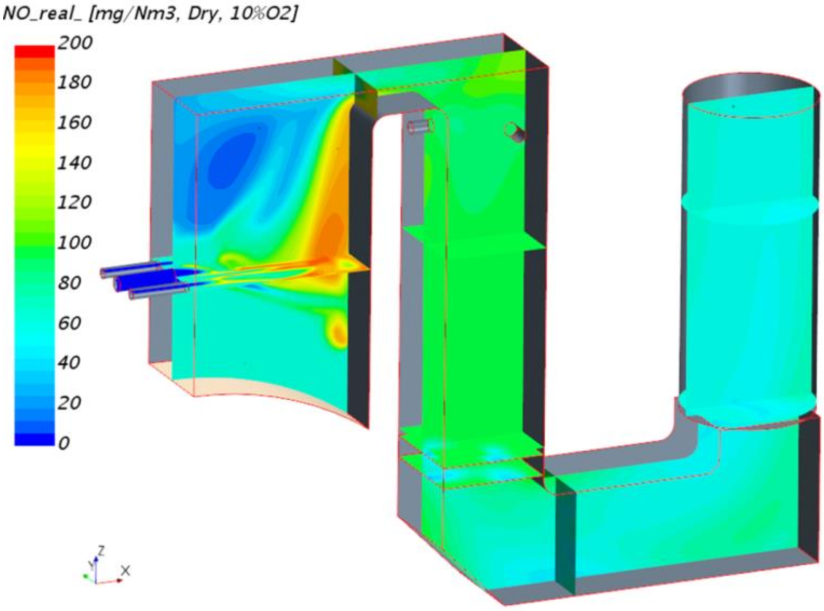


Figure 45: CFD calculation model of the CFD plant in Sindal with focus on NO$_x$

Figure 46: Sindal Biomass CHP plant at the official opening, September 15th, 2018

Figure 47: chairman of the board, Mr. Bjarne Christensen, welcomes the Danish Minister of Energy, Mr. Lars Christian Lilleholt at the official opening of the biomass plant, September 15th 2018

The key parameters of the plant in Sindal are as follows:

- Input fuel (wood): 5.5 MW
- Power: 0.8 MW
- Heat: 5.0 MW
- NO_x: 100 mg/m^3
- CO: 20 mg/m^3
- Dust: 20 mg/m^3
- Load: 20 – 100 %

The Sindal plant was put into operation in June 2018. Due to the low demand of heating the plant has only been operating on low load: 10-30% load.

The initial results of the plant show that key parameters in table above have been accomplished. During the fall of 2018 an extensive measurement campaign will be made, and results of these measurements will be published.

5.2.6 Acknowledgements

EUDP – The Danish Energy Agency support program who have contributed with financial support

The Growth fund, who have contributed with financial support

The Danish Environmental Agency, who have contributed with financial support

The Ministry for Research and Innovation, who have contributed with financial support

6 References

[1] M. Salomón et al. 2011 / Renewable and Sustainable Energy Reviews 15 (2011) 4451–4465; Small-scale biomass CHP plants in Sweden and Finland; Elsevier 2011

[2] Viking Heat Engines 2017; July 2017 from www.vdg.no; 2017

[3] A. González et al. 2014; Review of micro- and small-scale technologies to produce electricity and heat from Mediterranean forests' wood chips Renewable and Sustainable EnergyReviews 43 (2015) 143–155; Elsevier 2014

[4] Liu H, Shao Y ,Li J. A biomass-fired micro-scale CHP system with organic Rankine cycle(ORC) – Thermodynamic modelling studies. Biomass and Bioenergy 2011;35:3985–94.; 2011

[5] Simbolotti G. 2007; Biomass for power generation and CHP. IEA energy Technology Essentials. Paris, France: OECD/IEA; 2007

[6] Heizung Lüftung Klimatechnik 1-2/2010

[7] Groß B., IZES GmbH (Institut für ZukunftsEnergieSysteme) (Hrsg.): Stromerzeugung mit Holz- Mikro-KW(K)K mit Stirlingmotoren für Wohngebäude und Kleingewerbe <50kWel; Zittau (GER), 12.05.2011. verfügbar unter: http://www.izes.de/cms/upload/pdf/V_Zittau_Holz_Stirling_GRO_2011.pdf; Stand: 21.05.2013.

[8] Groß, Tänzer 2010, Groß B., Tänzer G.; IZES GmbH (Institut für ZukunftsEnergieSysteme) (Hrsg.): „NANOSTIR" - Wärme, Kälte, Strom aus einer Anlagentechnik; 3. Deutscher Stirling Kongress, Stuttgart (GER), 25.02.2010.

[9] Zeiler 2008, Zeiler, M.; Publish-Industry Verlag GmbH (Hrsg.): Biomassebetriebene Stirlingmotoren; Magazin Kompendium Energy 2.0, Ausgabe 2008, S. 294-296; verfügbar unter http://www.energy20.net/pi/index.php?StoryID=317&articleID=122629; Stand: 17.05.2013.

[10] Padinger R., Enzinger P., Joanneum Research – Institut für Energieforschung (Hrsg.): Biomasse-Stirlingmotor am Ökopark Hartberg; NOEST (Netzwerk Öko-Energie Steiermark) ENERGY LUNCH; Graz (AUT); 30.01.2008.

[11] Groß B.: Jetzt kommen die Kleinen... KWK-Anlage als Scheitholzkessel/Stirling Kombination - Teil 1; Fachzeitschrift Sanitär+HeizungsTechnik, Ausgabe 7/2008; Krammer Verlag Düsseldorf AG; Düsseldorf (GER); 2008; S. 58-61.

[12] Groß B.: Jetzt kommen die Kleinen... KWK-Anlage als Scheitholzkessel/Stirling Kombination - Teil 2; Fachzeitschrift Sanitär+HeizungsTechnik, Ausgabe 8/2008; Krammer Verlag Düsseldorf AG; Düsseldorf (GER); 2008; S. 56-59.

[13] Stanzel K. W.; SPM (StirlingPowerModule) Energieumwandlungs-Gmbh (Hrsg.): Stirlingpowermodule Status Feldtests; Präsentation, 2007/2008; verfügbar unter: http://noest.all2web.at/news/docs/25706_Stanzel_3005EL.pdf; Stand: 21.05.2013

[14] Homepage of ÖkoFEN Forschungs- und Entwicklungs GmbH: http://www.okofen-e.com; Niederkappel (AUT); Stand: 13.08.2017

[15] BHKW-Forum e.V. (Hrsg.): Artikel „Sunmachine"; verfügbar unter: http://www.bhkw-infothek.de/bhkw-anbieter-und-hersteller/mikro-bhkw-ubersicht/sunmachine/; Stand: 27.05.2013.

[16] Meier S., Fraunhofer-Institut für Werkstoffmechanik (IWM) (Hrsg.): Zuverlässiger Alpha-Stirling-Motor für Mini-Blockheizkraftwerke; Projektbeschreibung; Freiburg (GER); 13.09.2012; verfügbar unter: http://www.iwm.fraunhofer.de/aktuelles/details/id/606/; Stand: 27.05.2013.

[17] Meier S., Fraunhofer-Institut für Werkstoffmechanik (IWM) (Hrsg.): 1. Zwischenbericht 3/2013: Zuverlässiger Alpha-Stirlingmotor (ZUMO); Freiburg (GER); März 2013.

[18] Schnetzinger R. et al; 2016; DEVELOPMENT OF COMBUSTION CONCEPT FOR BIOMASS PELLET DRIVEN STIRLING ENGINE; proceedings EUBCE 2016

[19] BRIDGWATER A.V. et al; book: Small and Micro Combined Heat and Power (CHP) Systems; ISBN: 978-1-84569-795-2; Biomass-based small and micro CHP systems © Woodhead Publishing Limited, page 453; 2011

[20] D. Maraver et al. 2013; Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters Applied Energy 102 1303–1313; 2013

[21] Alanne K, Saari A. Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. Renewable and Sustainable; Energy Reviews 2004;8:401–31; 2004

[22] M. Kaltschmitt, H. Hartmann, and H. Hofbauer, Energie aus Biomasse: Grundlagen, Techniken und Verfahren, 3rd ed. Berlin, Heidelberg: Springer Vieweg, 2016.

[23] HARRISON J.; book: Small and Micro Combined Heat and Power (CHP) Systems; ISBN: 978-1-84569-795-2; Stirling engine systems for small and micro combined heat and power (CHP) applications © Woodhead Publishing Limited, page 179 ff; 2011

[24] HARRISON J. 2014; Stirling engine; http://micro-chp.com/stirling_engine.htm; Page updated 7th February 2014

[25] CLEANERGY Homepage; http://cleanergy.com/about/#overview; 4th September 2017

[26] NUSSBAUMER T., et al, 2012; 12. Holzenergie-Symposium: Holzenergie-Nutzung in der Energiestrategie 2050. Tagung an der ETH Zürich am 14.September 2012, ISBN 3-908705-24-X Verenum Zürich 2012

[27] Energy Matters; December 2014; Micro-CHP potential analysis European level report; CODE2 – Cogeneration Observatory and Dissemination; INTELLIGENGT ENERGY EUROPE; December 2014

[28] Obernberger et al. 2017; Small-scale BM based CHP; Final project report; ERA-NET Bioenergy; http://www.minibiochp.eu/fileadmin/user_upload/public/ESC_Final-

ERANET_Report_Final.pdf; June 2017

[29] Zywica Grzegorz et al 2015; PROTOTYPE OF THE DOMESTIC CHP ORC SYSTEM: CONSTRUCTION AND EXPERIMENTAL RESEARCH; 3rd International Seminar on ORC Power Systems, October 12-14, 2015, Brussels, Belgium; 2015

[30] Qiu, G., Shao, Y., Li, J., Liu, H., Riffat, S.B., 2012, Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications, Fuel, 96: p. 374-382.

[31] ASME ORC 2015, 3rd International Seminar on ORC Power Systems, October 12th – 14th 2015, Brussels, Belgium

[32] Ancona M.A. et al. 2016; A Micro-ORC Energy System: Preliminary Performance and Test Bench Development; Energy Procedia; The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license; 2016

[33] G. Qiu et al. Expanders for micro-CHP systems with organic Rankine cycle/ Applied Thermal Engineering 31 (2011) 3301-3307

[34] Jradi M. et al 2014; Micro-scale ORC-based combined heat and power system using a novel scroll expander; Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK; International Journal of Low-Carbon Technologies 2014, 9, 91–99; The Author 2014. Published by Oxford University Press.

[35] Renewable Heating&Cooling European Technology Platform 2013; Stratetic Research and Innovation Agenda for Renewable Heating & Cooling; www.rhc-platform.org; Brussels, © RHC-Platform, 2013

[36] Weissinger_KWB_2014_ppt_europeanMarket_CHP_CEBC2014.pdf

[37] Heberle_ORC_FV_Jahrestagung_2012.pdf

[38] 2012-ORC-Module.pdf

[39] BHKW-Prinz; Beitrag von admin on 09/Jun/13 Kategorie BHKW-News, http://www.bhkw-prinz.de/button-energy-erneut-pleite-insolvenzverfahren-eroeffnet/3112; February 2018

[40] Steam Engines; http://www.spilling.info/products/steam-engines.html; February 2018

[41] K. Brinkmann; Moderne Dampfmaschinen; KASSELER SYMPOSIUM ENERGIE-SYSTEMTECHNIK 2001; FernUniversität Hagen, Elektrische Energietechnik 2001

[42] Mühlstein Jan; Unternehmen – SteamCell geht Dampf aus; Energie & Management GmbH; 25.11.2005; https://www.energie-und-management.de/free-archive/feview3/10901 2005

[43] SBZ 9/2003; Heizung; page 62 - 64; http://www.bosy-online.de/Mini-Dampftriebwerk.pdf

[44] Institut für Thermische Turbomaschinen und Maschinendynamik: Technologie-Portrait Kraft-Wärme-Kopplung. TU-Graz, 2002

[45] Neuhofer W. 2004; Technologiebewertung von dezentralen Erzeugungseinheiten; Master

thesis; Fachhochschulstudiengang „Infrastrukturwirtschaft" Karpfenberg; Energie-Control GmbH; Rudolfsplatz 13a; September 2004

[46] Information about the Horizon2020 Project „CHP - Upscaling and commercialization of a highly efficient wood pellets fired steam engine CHP for heat and power generation" http://www.fabiodisconzi.com/open-h2020/projects/196161/index.html

[47] Information about Steamergy; https://www.steamergy.de/unternehmen/; March 2018

[48] Biomass-based small and micro CHP systems; © Woodhead Publishing Limited, page 453; 2011

[49] G. FRIEDL 2010; Evaluating the Transient Behaviour of Biomass Based Micro-CHP Systems – Steam Piston Engine and Integrated Thermoelectric Power Generation; BIOENERGY2020+; published at the 18th European Biomass Conference & Exhibition; Lyon; May2010

[50] Zotter G. et al. 2017; BioPower - Strom- und Wärmegenerierung aus Biomasse mittels einer neuartigen Pellet befeuerten Mikro-KWK; FFG-project no. 843873; Publizierbarer Endbericht; Klima- und Energiefond; https://www.energieforschung.at/assets/project/final-report/20171221-BioPower-publEber-FINAL.pdf ; December 2017

[51] D.M. Rowe, Thermoelectrics Handbook: Macro to Nano, CRC Press, 2006

[52] J. D. König, "Thermoelektrik: Strom aus Abwärme, Thermoelektrische Generatoren machen Systeme energieautark und sparen Energie", Themeninfo I/2016,Energieforschung kompakt, BINE Informationsdienst, http://www.bine.info/fileadmin/content/Publikationen/Themen-Infos/I_2016/themen_0116_internetx.pdf ; 03.03.2018

[53] S. LeBlanc, "Thermoelectric generators: Linking material properties and systems engineering for waste heat recovery applications"; Sustainable Materials and Technologies, Volumes 1–2; 2014, Pages 26-35, ISSN 2214-9937

[54] Höftberger E. et al.; Grid Independent Pellet Stove with Integrated Thermoelectric Generators; 19th European Biomass Conference and Exhibition, 6-10 June, Berlin, Germany

[55] Moser W. et al.; A Biomass based Micro-Scale CHP System with Thermoelectric Generators; Bioenergy2020+ GmbH (former Austrian Bioenergy Centre GmbH); Central European Biomass Conference 2008

[56] Stiewe C., Müller E.; Anwendungspotential thermoelektrischer Generatoren in stationären Systemen Chancen für NRW; study commissioned by Ministerium für Innovation, Wissenschaft, Forschung des Landes Nordrhein-Westfalen; DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.; http://elib.dlr.de/100251/1/DLR-Studie_Anwendungspotenzial_Thermoelektrischer_Generatoren.pdf; 2014

[57] Mair C. et al 2015; Characterisation Method for Thermoelectric Power Modules; EST 2015 – Energy, Science & Technology International Conference and Exhibition in Karlsruhe; 2015

[58] E. Müller, C. Drasar, J. Schilz and W. A. Kaysser "Functionally graded materials for sensor and energy applications", Materials Science and Engineering A362, p. 17-39(2003)

[59] SUMEC GEOPOWER: http://www.sumecgeopower.com/de/45/technology/screw-steam-expander-power-generators, last access Nov. 7th 2017

[60] ALL-ENERGY: http://www.all-energy.co.uk/__novadocuments/54107?v=635375674540330000, last access Nov. 7th 2017

[61] Iezzi, M., et al.: Enabling solid biomass fired small scale cogeneration systems with the twin screw wet steam expander technology, 25th European Biomass Conference and Exhibition, 12 – 15 June 2017, Stockholm, Sweden http://www.etaflorence.it/proceedings/?detail=13724, last access July 11th 2018

[62] Hanjalic, K., Stosic, N., 1997, Development and Optimization of Screw Machines with a Simulation Model – Part II: Thermodynamic Performance Simulation and Design Optimization, Journal of Fluids Engineering, 119(3): 664 – 670

[63] Smith, I.K., Stosic, N., Aldis, C.A., 1996, Development of a Trilateral Flash Cycle System: Part 3: Design of High-Effective Two-Phase Screw Expanders, Proceedins of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2010(1): 75-93

[64] Read, M.G., Stosic, N., Smith, I.K., 2014, Optimization of Screw Expanders for Power Recovery From Low-Grade Heat Sources, Energy Technology & Policy, 1(1), 131-142

[65] Dall Energy, 2012: Environmental Technical Verification Report, http://www.etv-denmark.com/files/air/Dall%20E%20TEST%20REPORT.pdf, last access July 11th 2018

[66] Dall Energy, 2014: Biomass Thermal Oxidizer at Warwick Mills (film) plant, https://www.youtube.com/watch?v=LcBN7xeCOYA, last access July 11th 2018

[67] Dall [3] "Proving concepts", article in "Bioenergy international" 2013

[68] Dall [4] "Destruction of VOC in a Dall Energy Biomass Gasifier at Warwick Mills", Paper at IT3 conference, Houston, October 2015

[69] Schmid 1 Dietrich Vogel, Schmid AG energy solutions, dietrich.vogel@schmid-energy.ch Weiterentwicklung und Optimierung einer Heissluftturbine im kleineren Leistungsbereich (80 - 95 kW_{el}), Schlussbericht zum Forschungsprojekt im Auftrag des Bundesamt für Energie BFE, Forschungsprogramm Biomasse und Holz, CH-3003 Bern, 2017 https://www.aramis.admin.ch/Default.aspx?DocumentID=35202&Load=true, last access July 11th 2018

[70] Dr. Dragan Stevanović, INNOVATIVE BIOMASS POWER PLANT BASED ON PEBBLE-HEATER TECHNOLOGY AND HOT AIR TURBINE http://pebble-heater.com/PowerGen-Article.pdf

[71] Bluebox Energy: Hot air turbines, http://bluebox.energy/technology/mono/, last access July 11th 2018

[72] Forschungsförderungsfonds der Gewerblichen Wirtschaft (A): Project 843873, BioPower Strom- und Wärmegenerierung aus Biomasse mittels einer neuartigen Pellet befeuerten

Mikro-KWK, https://www.energieforschung.at/projekte/809/strom-und-waermegenerierung-aus-biomasse-mittels-einer-neuartigen-pellet-befeuerten-mikro-kwk, last access July 11th 2018

[73] Zweiler, R.; Doczekal, Ch.; Paar, K.; Peischl, G.: Energetisch und wirtschaftlich optimierte Biomasse-Kraft-Wärmekopplungssysteme auf Basis derzeit verfügbarer Technologien – Endbericht; Projektnr. 812771; 2. Ausschreibung Energie der Zukunft; Bundesministerium für Verkehr, Innovation und Technologie (BMVIT) (ed.); Vienna (AUT); 2008.

[74] Marinitsch G. and Kamenik-Lingitz.: Biomasse-CHP with updraft gasification and Stirling engine; conference proceedings of the 12. Holzenergie-Symposium in 2012 at the Federal Institute of Technology ETH Zurich

[75] CODE2 – COGENERATION OBSERVATORY AND DISSEMINATION is co-funded by the European Commission (Intelligent Energy Europe – IEE) and will launch and structure an important market consultation for developing 27 National Cogeneration Roadmaps and one European Cogeneration Roadmap. This study contains the background and methodology used to project the European micro-CHP market until 2030.

[76] STEAMERGY GMBH & CO: Weltneuheit Dampfheizkraftwerk, http://www.energiesparmesse.at/ne13/index.asp?pn=6170028&ly=9&nid=2153, March 2018, last access July 11th 2018

[77] Hegele D.: Einbindung von Stirling-Motoren in Stückhoolz- und Pelletskessel, Hoval http://www.akvt.de/ft2011/unterlagen/A4-Hoval.pdf, Jan. 2012, last access July 11th 2018

[78] BHKW-Kenndaten ASUE/BHKW-Infozentrum (Datenbank-Stand 03.08.2016)

[79] BHKE-Infozentrum Rastatt: BHKW-Hersteller und BHKW-Module, www.bhkw-kenndaten.de, Aug. 2016, last access July 11th 2018

[80] Schmid Energy: Moving grate firing system with integrated hot air turbine http://www.schmid-ag.ch/files/attachments/Heissluftturbine_Schmid_ENG_635343005651285014.pdf, last access July 11th 2018

[81] Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK: Weiterentwicklung und Optimierung einer Heissluftturbine im kleineren Leistungsbereich (80 - 95 kWel) https://www.aramis.admin.ch/Default.aspx?DocumentID=35202&Load=true, March 2017, last access July 11th 2018

[82] Qnergy: www.qnergy.com/about-qnergy/, last access July 11th 2018

[83] Inspirit Energy: The inspirit charger, http://www.inspirit-energy.com/story/the-inspirit-charger, last access July 11th 2018

[84] Frauscher Thermal Motors website: http://www.frauscher-motors.com/, last access November 15th 2018

[85] Boloy RAM., Silveira JL., Tuna CE., Coronado CR., Antunes JS.: Ecological impacts from

syngas burning ininternal combustion engine: Technical and economic aspects. Renew Sustain Energy Rev 2011; 15:5194 – 201.

[86] Ahrenfeldt J., Henriksen U., Jensen TK., Gøbel B., Wiese L., Kather A., et al.: Validation of a continuous combined heat and power (CHP) operation of a two-stage biomass gasifier. Energy Fuel 2006; 20:2672 – 80.

[87] Ahrenfeldt J.,Thomsen TP., Henriksen U., Clausen LR.: Biomass gasification cogeneration – A review of state of the art technology and near future perspectives. Appl Therm Eng 2013; 50:1407 – 17.

[88] Assanee N., Boonwan C. State of the art of biomass gasification powerplants in Thailand. Energy Procedia 2011; 9:299 – 305.

[89] Centre Tecnològic Forestalde Catalunya C., Catalonia TFC of. Presentació de la planta pilot de cogeneració amb gasificació de biomassa forestal del CTFC 2012.

[90] Coronado CR., Yoshioka JT., Silveira JL.: Electricity, hot water and cold water production from biomass. Energetic and economical analysis of the compact system of cogeneration run with woodgas from a small downdraft gasifier. Renew Energy 2011; 36:1861 – 8.

[91] Warren T., Poulter R., Parfitt R.: Converting biomass to electricity on a farm-sized scale using downdraft gasification and a spark–ignition engine. Bioresour Technol 1995; 52:95 – 8.

[92] Lee U., Balu E., Chung JN.: An experimental evaluation of an integrated biomass gasification and power generation system for distributed power applications. Appl Energy 2013; 101:699 – 708.

[93] Qui G. et al.: Fuel 96 (2012) 374-382, www.elsevier.com/locate/fuel, last access July 11th 2018

[94] Viking Heat Engines: CraftEngine, the most flexible ORC waste heat recovery system on the market, www.vikingheatengines.com/products, last access July 11th 2018

[95] Orcan Energy: Efficiency pack 20.30 and EP 05.15, www.Orcan-energy.de, last access July 11th 2018

[96] Sara Goudarzi: Reinventing the Steam engine, www.poweringag.org/news-events/news/reinventing-steam-engine, 2013, last access July 11th 2018

[97] VEP Fördertechnik, Green Steam, www.vep.at, last access July 11th 2018

[98] ÖKOFEN: Strom und Wärme - ein Pelletskraftwerk für jeden Leistungsbereich, www.okofen-e.com/de/pellematic_smart_e/, last access July 11th 2018

[99] Microgen engine coproration: Free piston Stirling Engine, www.microgen-engine.com, last access July 11th 2018

[100] Frauscher Thermal Motors: Newletter 01/2014, www.frauscher-motors.com, last access July 11th 2018

[101] Qnergy: Renewable, Reliable, Resilent, www.qnergy.com, last access July 11th 2018

[102] Pellet stove with TEG 400, picture by courtesy of BIOENERGY2020+ GmbH, www.bioenergy2020.eu

[103] Pellet boiler with TEG 250, picture by courtesy of BIOENERGY2020+ GmbH, www.bioenergy2020.eu

[104] Heliex Power: Generate low cost energy from your steam, www.heliexpower.com, last access July 11th 2018

[105] Enogia: Convert your low-temperature heat into electricity, www.enogia.com, last access July 11th 2018

[106] Schmid Energy Soutions: Voller Energie, www.schmid-energy.ch, last access July 11th 2018

[107] European Patent Office: Biomass – an ancient source of energy gets a new twist, http://www.epo.org/learning-events/european-inventor/finalists/2011/bentzen.html, Oct. 2011, last access July 11th 2018

[108] Miljøstyrelsen: Clean Tech-prisen går til biomasseovn, http://mst.dk/service/nyheder/nyhedsarkiv/2011/sep/clean-tech-prisen-gaar-til-biomasseovn/, last access July 11th 2018

[109] CNN: One man's waste, another man's energy, http://edition.cnn.com/videos/business/2013/10/24/spc-make-create-innovate-biomass-power.cnn, last access July 11th 2018

[110] The New York Times: Denmark, a Green Energy Leader, Slows Pace of Its Spending, http://www.nytimes.com/2015/12/06/world/europe/denmark-a-green-energy-leader-slows-pace-of-its-spending.html?_r=0, last access July 11th 2018

[111] OTAG GmbH: lyon-Powerblock, http://www.bhkw-prinz.de/otag-gmbh-lion-powerblock/149, last access July 11th 2018

[112] ORMAT: Powered by nature, harnessed by us, http://www.ormat.com/en/home/a/main/, last access July 11th 2018

[113] ELECTRATHERM: Reduce or eliminate flaring, https://electratherm.com/, last access July 11th 2018

[114] INFINITY TURBINE: Introducing the Radial Outflow Turbine Generator - Organic Rankine Cycle - ORC Turbine, http://www.infinityturbine.com/, last access July 11th 2018

[115] Village Industrial Power, Cambridge, MA, USA: http://villageindustrialpower.com/, last access July 26th 2018

[116] V.E.P. Fčrdertechnik Ges.m.b.H, Loipersbach (A): www.vep.at, last access July 26th 2018

[117] Spilling Technologies GmbH, Hamburg, (D): http://www.spilling.info/products/steam-engines.html, last access July 26th 2018

[118] Infinity Turbine LLC, Madissn, Wi, USA: www.infinityturbine.com, last access July 26th 2018

[119] Ormat Technologies, INC., Reno, Nevada, USA: www.ormat.com, last access July 26th 2018

[120] Electratherm, Reno, Nevada, USA: www.electratherm.com, last access July 26th 2018

[121] Freepower Ltd., Andover, Hampshire, UK: www.freepower.co.uk, last access July 26th 2018

[122] GILLES Energie- und Umwelttechnik GmbH & Co KG, Gmunden, A http://www.gilles.at/en/company, last access July 26th 2018

[123] ERA-Net project: https://www.chalmers.se/en/projects/Pages/Development-of-innovative-small-QmicroQ-scale-biomass-based-CHP.aspx, last access July 26th 2018

[124] Viking Development Group, Kristiansand, Norway: www.vdg.no, last access July 26th 2018

[125] Mini Green Power, Hières, F: http://www.minigreenpower.com/mini-centrale-verte, last access July 26th 2018

[126] Thermoelect GmbH, Hansestadt Wismar, D: http://he-energy.gmbh/de/Start.html, last access July 26th 2018

[127] AEBIOM Statistical report 2017

[128] IEA Bioenergy Task 32 Report: http://www.ieabcc.nl/publications/TEA_CHP_2015.pdf, last access July 26th 2018

[129] Padinger R. et al.: Stabilisierung des Stromnetzes mit Hilfe eines Verbundes von Biogasanlagen (Voltage stabilization by central reactive power control of biogas power plants), project report, JOANNEUM RESERACH Graz, 2008, in the frame of the Austrian research program "Energiesysteme der Zukunft", project no. 811253, https://nachhaltigwirtschaften.at/de/edz/projekte/stabilisierung-des-stromnetzes-mit-hilfe-eines-verbundes-von-biogasanlagen.php, last access July 26th 2018

[130] ETIP Bioenergy European Technology and Innovation Plattform: Biofuel fact sheet, Biomass CHP facilities (in press)

IEA Bioenergy

Energy Technology Network

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

Contact us:
www.ieabioenergy.com/contact-us/