SET-UP AND PILOT OPERATION OF AN IN-HOUSE DEVELOPED BIOMASS ORC µCHP IN THE CZECH REPUBLIC

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ABSTRACT

Microcogeneration (µCHP) systems have been tried with various technologies including ORC and with many attempts for commercialization. The requirements of noble fuels (e.g. natural gas), high price, and unsuitable business models together with legal and other obstacles have in most cases limited its successful deployment.

A unique ORC based µCHP system named for biomass combustion (including low quality biomass) named Wave is presented in this paper. The developed system is first shown in scope of the previous research and development. The issues that have arisen with the operation of the pilot installation in comparison to the laboratory experimental unit including technical, legal and economic aspects, are outlined. This is followed by a description of the technical parameters and the applied technologies of the system. Operation parameters in given regimes are shown based on the field data from the pilot application as well as overall integral quantities in the first heating season. The operation of the pilot commercial unit is not yet without any flaws and several problems occurred. These are presented in this paper and are a subject of an intense development.

Commercialization of µCHP ORC units is limited by several economic and political factors. The different paradigm that authors adopted shows that economic performance cannot be the only parameter for investment evaluation, but investor needs to assess additional benefits from the µCHP system. This point is discussed in a separate chapter.

1. INTRODUCTION

Distributed microcogeneration (µCHP) units and small scale waste heat recovery (WHR) are one of the key concepts for the sustainable future of energetics and for smart grids. Within decentralization, the energy systems are gradually decreasing in nominal power output and moving towards modularity. This is the case also for combined heat and power systems with number of µCHP systems on the market as well as attempts for their commercialization. These systems are usually based on fuel cells, reciprocating internal combustion engines and microturbines for systems with internal heat input and Stirling engines, steam Rankine and organic Rankine cycle (RC and ORC) for systems with external heat input. There are other theoretically applicable technologies including thermodynamic cycles (inverted Brayton cycle, absorption power cycle), or direct conversion (thermoelectric, thermophotovoltaic, thermionic) which are in phase of early research still have to undergo a long journey until reaching the market potential. However, ORCs are the unrivalled technical solution for generating electricity from low-medium temperature heat sources of limited capacity. (Macchi and Astolfi, 2016)

When focusing on systems with electrical output in the order of less than 10 kW_e, most of the systems on the market or with attempts for commercialization however consume noble liquid or gaseous fuels. This has been the case also for number of systems with external heat input such as Stirling engines (Harrison, 2003; Thombare and Verma, 2008; Alanne *et al.*, 2010; Hachem *et al.*, 2018) and Rankine cycles (Dentice d'Accadia *et al.*, 2003; Alanne and Saari, 2004; Kuhn, Klemeš and Bulatov, 2008;

Bianchi, De Pascale and Spina, 2012; Pereira *et al.*, 2018). Number of such systems utilizing solid and lower quality fuels is very low, even though the supply of those fuels can be significant and at quite a low price. **Table 1** contains a nearly-exclusive list of units and projects for μCHP systems operating with solid fuels (biomass) and having power output < 30 kW_e. Systems integrating biomass utilization with the power production in a single product were very few and are mostly discontinued. Currently there are new companies with micro ORC modules, but the biomass boiler and accessories have to be eventually handled separately by customer. It can be concluded, that there is a niche and significant potential for new integrated systems based on biomass combustion, assuming that such system will manage to overcome technical and economic obstacles.

Table 1: List of units and projects for < 30 kWe μCHP systems for solid fuels (biomass)

Product or project (manufacturer)	Type of technology	El. output (kW)	Ther. output (kW)	Status	References
Stirling power module (KWB - Kraft und Wärme aus Biomasse GmbH)	Stirling as additional module for biomass boiler	1	15	Project definitely cancelled in 2010 as too expensive after field tests	http://www.kwb.at/
Sunmachine (Öko-Energiemaschinen Vertriebs GmbH)	Stirling + pellet combustion	3	10.5	Sold as pellet CHP unit, discontinued ~ 2012	http://www.sunmachine.at/
ML1000, ML3000 Genoastirling S.r.l.	Stirling + combustion*	1.1 - 3.3	10 - 19	Offered as product	http://www.genoastirling.com/
DD4-E (Stirling DK)	Stirling (+ gasification)	35	140	Sold as woodchip CHP unit, introduced to the market without any significant success	http://www.stirling.dk/
BioGen (Stirling Technology, Inc.)	Stirling + gasifier integrated unit	1	8.5	Offered as product	http://www.stirling-tech.com/
HRU-5, HRU-25 (Enerbasque)	ORC module only*	5, 25	n.a.	Offered as product, has references	http://enerbasque.com
10LT-40LT (Enogia)	ORC module only*	10-100	n.a.	Offered as product, has references	http://www.enogia.com/
Rank® HTC1 and other (Rank)	ORC module only*	25 - 45	200-350	Offered products from 1 kW_e for lower temperatures, has references	http://www.rankweb.es/
Kaymacor ORChidea	ORC cogeneration; pellet combustion	2-24	15-240	Enters the market, offers variety of modifications and applications from 2 to 24 kWe	https://www.kaymacor.com/en/
Viking Development Group (CraftEngine)	Waste heat recovery and biomass fired ORC, engine from automotive	2-12	30-150	Five patents for the biomass fired ICE ORC, several references	http://www.vikingheatengines.com/

*cogeneration CHP is only 1 option of use

A perspective integrated system is presented in this work, particularly a biomass fired μCHP ORC system named *Wave* which is in the phase of a first commercial prototype pilot application. This paper is a follow-up on the 10 years of previous research and development of μCHP ORC systems at Czech Technical University in Prague. (Mascuch *et al.*, 2018). The development includes a number of predecessor units and its modifications. The main aim and focus has been ever since the beginning of the project at the application and towards commercialization of WHR and biomass μCHP ORC units of under 10kW_e scale. Four different concepts of ORC units were experimentally tested. First proof-of-concept unit with isopropylbenzen (cumene), a recuperator and a thermal oil loop was followed by three generations of units with hexamethyldisiloxane (MM), a spiral wound flue gas heat exchanger and an in-house developed rotary vane expander. The current version of the ORC unit is a result of reiterations from several dead ends in the design. The previous research done in this project was extensively discussed and summarized at the ORC 2017 conference in (Mascuch *et al.*, 2017) and last laboratory unit in (Mascuch *et al.*, 2018).

As this μCHP ORC unit was being developed with an intention to be commercialized, the ORC system has to be set within boundaries of a real application, where the optimal thermodynamic performance is only one of the many optimization criteria. Hence, selected concepts and design parameters slightly differ in the context of numerous other research works.

A brief overview of the technologies and the technical parameters of the unit are presented. Major focus here is on reporting the issues emerged with the installation and set-up, experience from the pilot operation together with the field data and the parameters from the operation. Finally, the presented economic considerations show which situations and parameters should be considered (and are different from previous μCHP biomass units) to make application of such system feasible and not to follow the cases of unsuccessful projects in the past.

2. BIOMASS FIRED ORC μCHP SYSTEM

2.1 Technology and parameters

The technology is based on a laboratory ORC unit located at The Laboratory of Organic Rankine Cycles and their Applications (LORCA) in the University Centre for Energy Efficient Buildings (UCEEB) at the CTU in Prague that has been originally described in (Mascuch *et al.*, 2018). Since then there has undergone further development of its components and slight changes in the overall configuration. Major improvements were done regarding the control systems. Due to the general similarity with previous system, here are mentioned only the main parameters, features and major achievements and improvements.

To briefly describe the unit, biomass is supplied from the hopper into the combustion chamber by a screw conveyor together with the combustion air. Flue gases exit the combustion chamber into the mixing chamber for mixing with recirculated flue gas. The temperature at the chamber outlet is kept constant on a nominal value of 650°C by the flue gas recirculation fan, which rotation speed is regulated by a variable frequency drive. It blows the flue gases back into the combustion chamber for reducing the temperature of the combustion process and reducing the thermal NOx production. The flue gases then further continue into spiral wound heat exchangers, which heat up and evaporate the working fluid – hexamethyldisiloxane (MM). Based on the previous experience, the working fluid was selected with respect to its high thermal stability, relatively moderate admission pressures, liquid state under atmospheric conditions, low flammability and toxicity and general environmental friendliness. (Keulen *et al.*, 2018) The whole process in the μCHP ORC unit is displayed in the process flow diagram in **Figure 1.**

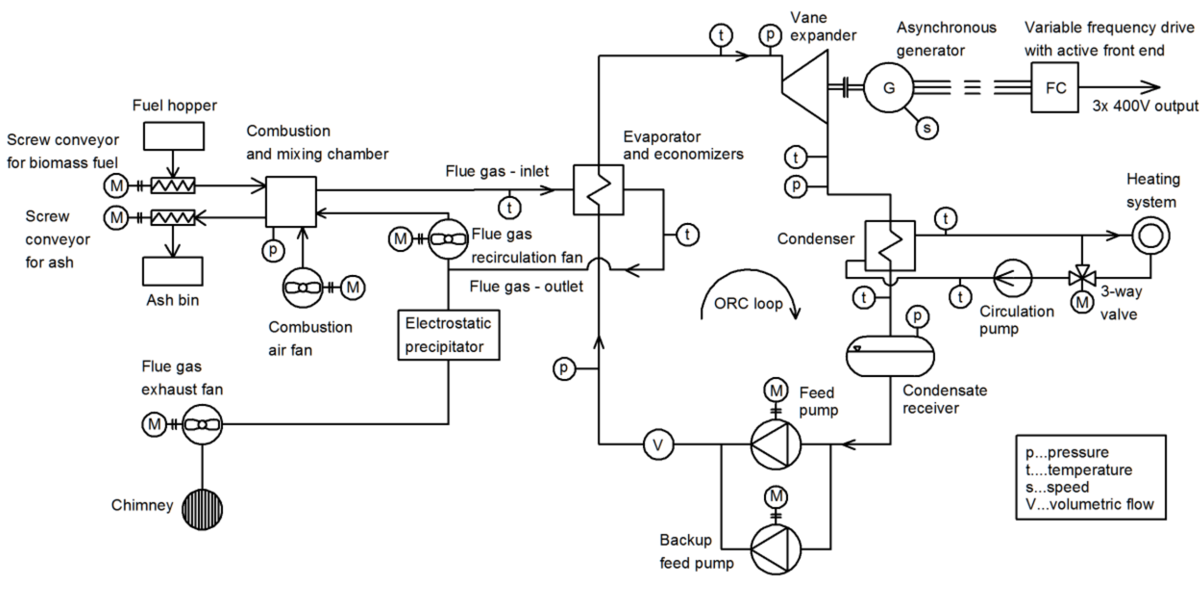

Figure 1 Process flow diagram of the pilot μCHP ORC unit Wave

The system runs without any intermediate fluid loop as the direct heating of MM is sufficiently safe. MM evaporates and is superheated by 5K, which is the main control parameter of the system, transformed by PID regulator into pump speed control signal. The organic vapour enters the rotary vane expander where it expands and produces mechanical work. The torque from the expander to an asynchronous generator is transferred via a neodymium magnetic coupling. The condenser is cooled down by the cooling water supplied from the building and the hot water leaving the condenser is then used in the building for the central heating. The system is operated without any recuperative heat exchanger, mainly for simplicity of the system. Nominal performance and overall parameters of the unit are shown in **Table 2**. The unit is depicted (partial section of the containerized system 3D model and installation photography) in **Figure 2**.

Table 2: Nominal parameters of the µCHP ORC unit

Net el. Output	2	kW_e
Gross el. output	3.5	kW_e
Thermal output	50	kW_{th}
Nominal heating water T	80 / 60	°C
Wood pellets consumption	14	$Kg.h^{-1}$
Overall efficiency	80	%
Dimensions	4 x 2.8 x 2.44	m
Weight	5000	kg

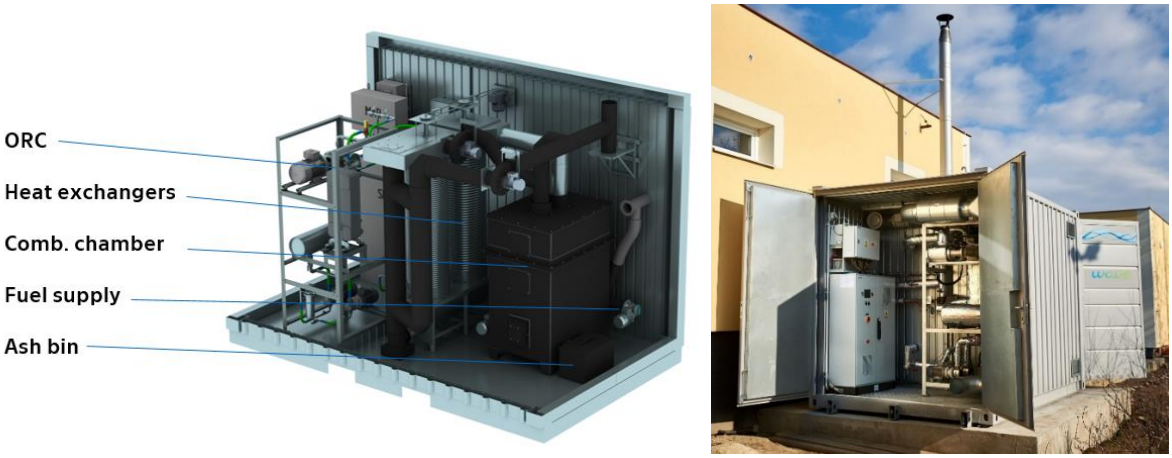

Figure 2: A render and a photography of the µCHP ORC integrated unit

2.2 Pilot installation issues and requirements

The conversion of a laboratory unit (similar to the one described in (Mascuch *et al.*, 2018)) into a field application faces number of technical as well as legal issues. The technical issues consist of especially transportation, automation of operation and control and connection to the local utilities.

Transportation analysis led to a decision, that containerized solution is the only feasible option. Not only it meets all the mechanical and safety requirements and is very mobile, but a µCHP unit placed in a container has less legal requirements to be tackled.

There are several specific legal requirements and standards that each µCHP must follow and comply with. Such requirements have to be tackled as an integral part of the design process and cannot be neglected. The legal framework of µCHP ORC units in the Czech Republic was discussed (Mascuch *et al.*, 2018). As this unit is primarily developed for the Czech market, the legal framework complies with the Czech laws, government decrees and industrial standards, but at least in the EU countries, these requirements differ only marginally.

A major advantage for small systems is that devices of less than $10kW_e$ installed electrical capacity can be operated without a need for an electricity production license in the Czech Republic. These micro-sources can be connected to the grid in "simplified" process. Another limitation put on µCHP units is the flue gas emission limits, namely the CO content, total organic carbon (TOC) and fly ash pollution. As µCHP ORCs are not legally considered to be "biomass boilers" but "stationary sources of pollution", they do not have to fulfil the NO_x limits. Also, any device on the market has to follow the general safety and construction requirements. Many administration processes are much simpler for micro devices, be-it e.g. the pressure and explosion safety, the manufacturer still has to provide the CE certificate for the product. In addition, the risk of leakage to atmosphere needs to be prevented as the working fluid might damage the ozone layer or pollute the atmosphere. The siloxane is however only moderately flammable. Moreover, it is safe from the ODP and GWP point of view and only little toxic.

2.3 Operation data

The operation regime of the unit is to run in nominal conditions or close to them all the time, starting and shutting down the system based on the actual heat demand and state of charge of a hot water storage buffer. Averaged parameters in conditions at steady state illustrating the operation regime of the ORC are shown in **Table 3**. Please note that in the CHP regime the heat rejection conditions of the cycle are at nearly constant temperature for most of the time.

Table 3: Steady state nominal operation parameters; averaged over a one hour of operation

Parameter	Value	Units
Biomass combustion		
Flue gas temperature at evaporator inlet	650	°C
Flue gas temperature at evaporator outlet/economizer inlet	275	°C
Flue gas temperature at economizer outlet	158	°C
ORC		
Expander inlet pressure	510	kPa
Expander inlet temperature	177	°C
Expander inlet superheating	10	K
Expander outlet pressure	55	kPa
Expander outlet temperature	153	°C
Condenser outlet temperature	55	°C
Volumetric flow rate of liquid MM	0,19	$l \cdot s^{-1}$
Thermal output		
Water inlet temperature	56	°C
Water outlet temperature	73	°C
Other		
Generator rotational speed	3020	rpm
Heat output	50	kW
Generator power output	2507	W
Net electric power output	1550	W
Expander isentropic efficiency	46	%

Please note that the accuracy, precision and sensor types of each quantity was reported in previous paper about the laboratory unit and are the same for the pilot commercial one. (Mascuch *et al.*, 2018)

Operation data are available from the first heating season (2018/19) of the system. Over the period of 5 months, the system operated for over 1600 hours in total. The major global parameters are summarized in **Table 4**.

Table 4: Overall operation data from the first heating season 2018/2019

Parameter	Value	Units
Total operational time	1600	hrs
Number of starts	335	-
Total heat produced	235	GJ
Total gross electricity produced	654	kWh
Total own electricity consumption	984	kWh

Please note that the accuracy, precision and sensor types of each quantity was reported in previous paper about the laboratory unit and are the same for the pilot commercial one. (Mascuch *et al.*, 2018)

The overall negative electricity production balance was mainly caused by the damage of the vanes in the rotary vane expander. For this reason, the ORC unit was operated for hundreds of hours producing only heat to satisfy the heat demand of the end user. Thanks to the construction of the rotary vane expander, it is possible to operate the CHP unit while the expander is not operational – the rotor of the RVE is stationary and the whole unit is operated in the “heat only” regime. The damage of the tips of the composite vanes is clearly shown on the **Figure 3**. This issue is currently a subject of an intense research and development.

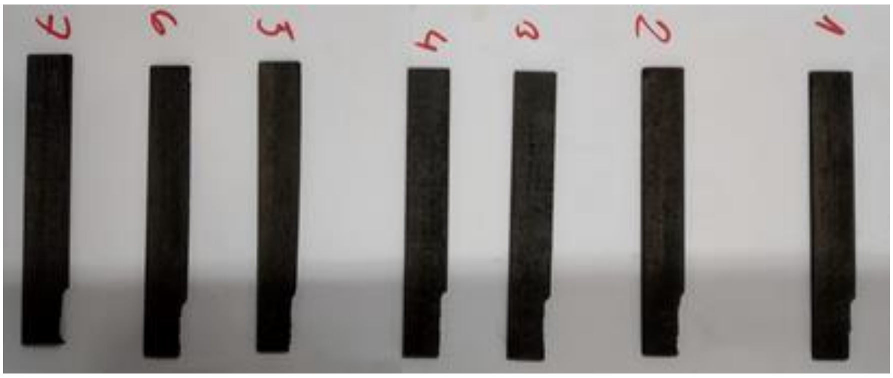

Figure 3: Damage of the tips of the vanes

2.4 Experience from the set-up and operation

Microcogeneration unit Wave was installed as a part of the more complex energy solution including solar PV, battery storage and heat storage in a pilot commercial application in a small Czech village Mikolajice, where it supplies heat and electricity for municipal buildings. The heat source exploited there are wood pellets, because of a steady and cheap supply in village proximity. The fuel analysis is summarised in the **Table 5.**

Table 5: Fuel analysis of the wood pellets burnt in the μCHP ORC unit Wave in Mikolajice

Wood pellets type A1 (ENplus A1 CZ007 standard)	Value	Units
Water content W_{tr}	2,66	%
Ash content A_r	0,2	%
Combustible Sulphur content S_{cb}	0,018	$\%_{mass}$
Higher heating value HHV	19 110	$MJ.kg^{-1}$
Lower heating value LHV	17 950	$MJ.kg^{-1}$

Note: The fuel analysis was conducted on the 4th of February 2019

After the transport to the location, there were still several challenges left to be solved before the unit could have been started. It was mainly the connection to the local heating system, electrical grid, setting up the chimney, connecting the fuel conveyor to the wood pellet storage, insulating final pieces of pipelines, and finally setting up a PLC for measurement and control.

Non-optimal settings of some PID controllers resulted in initial issues with the control of the combustion process, but these problems were easily solved *in-situ*. Isentropic efficiency of the expander is slightly lower than at the laboratory unit. This as well as the limited life of the vanes is a subject of intensive development at the moment. Another issue that occurred during the first heating season was concerning the automatic cleaning system of the flue gas heat exchanger. The mechanism used in this unit is a system of rotating chains that clean the surface of the heat exchanger from the fly ash mechanically by rubbing the chains against the metal surface. These chains however got entangled and stuck after several hundreds of operating hours and had to be untangled by hand. Even such small issues lead to relatively high expenditures as the unit is operated in a rather distant area of the country and tweaking just a tiny problem may cause severe operational costs. Therefore, solving and preventing challenges that obstruct an automatic operation of the CHP unit are of the upmost priority.

The results of the authorized emissions measurement conducted on the μCHP ORC unit are reported below in **Figure 4.** As mentioned above, any so called stationary air pollution source has only three emission limits to comply with: solid fly ash particles, CO and TOC.

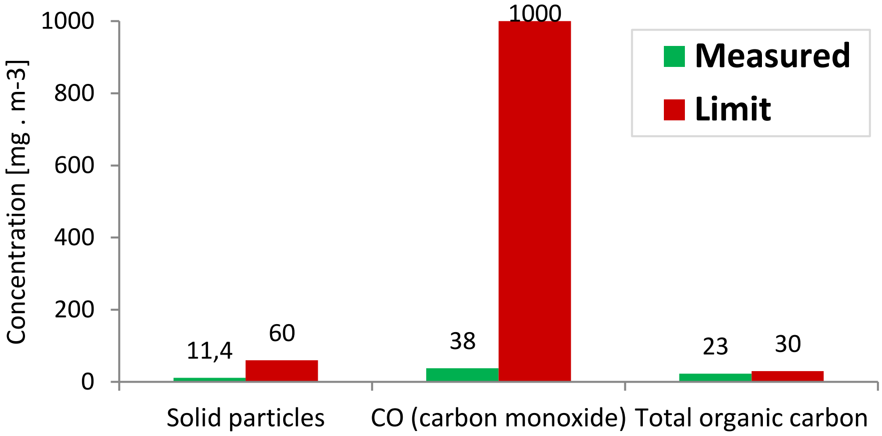

Figure 4: Results of the authorized emission measurements

3. ECONOMIC CONSIDERATIONS

The issue of the economic efficiency of renewables is in general a "multi-layered" problem. Nowadays commercial investors typically prefer lowest capital cost option for satisfying energy demands, regardless of long term benefits (Mascuch, Novotny and Tobias, 2018). When investors are more sensitive to operating costs (e.g. municipalities), just a simplified evaluation of the economy of investments based on a simple return on investment using current prices of energy and technology is not sufficient. The reason is the risk of excluding important effects that the investment might bring to investors' economy. Performing the cost-benefit analysis brings several advantages in a broader sense, including not only financial but also non-financial aspects of the project in the medium and long term. The benefit in the energy independence, stability and security that the use of renewables can bring may be shown on examples such as that the local fire brigade would have the ability to operate through its own energy resources in situations where the municipality is without electricity.

A good economic evaluation with the quantification of cash flows is then just an auxiliary indicator of how the realization of the investment is reflected within the particular part of the investor budget. It is ideal to process the above-mentioned cost-benefit analysis with the evaluation of the broader relationships the investor has. The cost benefit analysis, especially for a customer as the municipal investor, can draw attention to the fact that while the natural gas costs leave the municipality in the form of payments "outside", the biomass might instead be produced by local technical services and can have a positive effect on the local economy (even to finance the waste disposal and sorting). If the implementation of the biomass project achieves comparative final heat prices for the customer (considering the investment), the funds do not flow "outside" the municipality and the value of the property of the municipality or the company established in such project increases.

In general terms, the investments with low investment costs usually drain future budgets of the investor through high operating costs to energy suppliers. For investments with higher investment costs, i.e. usually those based on renewable energy sources, the operating costs are significantly lower, and the investment might increase the value of the investor's assets. The character of the investor, its point of view on the possibilities of investment, preferences, portfolio management and risk management influence the decision of investment to decentralized sources much more than only technical parameters of the available options.

For our case, the definition of benchmark option and total cost of energy production led to a specific point of view on the investment. Once investor decided to use biomass, benchmark for CHP system is a wood chips boiler. Then if payback period is the main criterion, extra cost of CHP system compared to wood chips boiler price has to be returned in requested time. This is because wood chips boilers do not offer payback to the investor, if existing boiler at the end of life needs to be replaced and they have roughly similar efficiency. Specifically, in the case presented at this paper, a basic cost of the installed system was around 95 000 EUR. Current plans already consider a development of a larger unit with thermal output of 120 kW_{th}, where thermodynamic parameters should be better and basic installation cost of the system would rise only slightly to 120 000 EUR (all without VAT).

5. CONCLUSIONS

Integrated biomass fired micro-cogeneration units may have significant application potential when the parameters are set well to make an economically interesting alternative to automatic biomass boilers. Presented μCHP ORC unit developed at CTU in Prague has a great potential for fulfilling such requirements. We describe a conceptual approach, technology, and parameters and performance from the pilot operation together with encountered issues for further development and improvements. Economic considerations show that such unit should be marketed rather as an automatic boiler for cheap biomass with a positive electrical balance rather than typical (reciprocating engines based) cogeneration units with higher electrical efficiency but much more expensive noble fuels. Furthermore, economic performance should be considered together with additional benefits. With these considerations there appears perspective niche market for these systems.

NOMENCLATURE

CHP	Combined heat and power
ORC	Organic Rankine cycle
CO	Carbon monoxide
TOC	Total organic carbon
PLC	Programmable logic controller
PID	Proportional, integral, derivative (controller)
R&D	Research and development
MM	Hexamethylendisiloxane
WHR	Waste heat recovery
CTU	Czech Technical University in Prague
UCEEB	University Centre for Energy Efficient Buildings
VAT	Value added tax

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