SCALING-UP A BIOMASS FIRED MICRO-CHP ORC FOR BETTER PERFORMANCE TOWARDS COMMERCIALIZATION

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ABSTRACT

Microcogeneration utilizing Organic Rankine cycle technology is seen as a technology of vast potential, but commercialization attempts of many systems have shown how challenging it is to transform laboratory results into competitive products. Throughout the development, the authors' collective focus on cogeneration from biomass, including very low grade one, for which organic Rankine cycle power systems appear as a suitable choice. In the past, at the Czech Technical University, the authors developed a 50 kW_{th} 2 kW_e unit that has undergone an on-site pilot installation. The economic parameters were however for many other applications prohibitive, especially with respect to the new legal requirements for biomass combustion.

Therefore, in order to improve the economic performance, the system has been scaled up to 120 kW_{th} and 6.2 kW_e. This manuscript discusses the process of scaling up, designing, assembling and operating the upscaled combined heat and power unit. It includes modifications of previously applied technologies, especially regarding the boiler, an in house designed rotary vane expander and the overall system configuration. Furthermore, the authors present a comparison of the operational parameters of the new 6.2 kW_e unit with the previous smaller 2 kW_e unit, as well as a comparison of the implemented rotary vane expanders as a specific feature of the design. The comparison is performed on several thousand hours of experimental data for both units. From the total net combined heat and power production efficiency standpoint, the larger unit exceeds the former one by five percentage points, reaching 89%, even though the expander performance is slightly poorer with a nominal isentropic efficiency of 56%. However, the economic performance of the upscaled unit excels in comparison with the smaller one. Economic evaluation with a reference 120 kW biomass boiler concludes that an increase of the capital cost of the boiler by one third justifies the investment into the ORC CHP module.

1 INTRODUCTION

Organic Rankine cycle (ORC) power systems became an unrivalled technical solution and an industrial standard in several applications, such as low temperature heat utilization in geothermal systems, combined heat and power (CHP) systems in the scale of several *MW* down to hundreds of *kW* or waste heat recovery (WHR) power systems down to dozens of *kW*. (Colonna *et al.*, 2015; Macchi and Astolfi, 2016)

When focusing on the micro scale or even domestic CHP ORC with electrical output in the order of less than 10 *kW,* many laboratory units and prototypes have been built and tested. Regardless of these R&D efforts, these micro scale systems mostly have not seen commercialization or the commercialization phase has not been reported in any journals. The rest have not yet been proven to be economically feasible or are very scarce on the market, mainly because their installations face economic barriers with economy-of-scale. Downscaling the ORC power systems to micro scale results in high specific costs associated with low initial production quantities and large cost per installed kilowatt. (Padinger, Aigenbauer and Schmidl, 2019)

The research and development in these laboratory scale µCHP ORC units, as mentioned above, has been very vital in the last decade. The major focus has been on the expander technology, working fluid selection as well as experimental investigations. Table 1 presents some of the experimental biomass-fired micro scale ORC power systems available in the literature and summarizes the main results from the measurements. This research is, however, often decoupled from the commercialization of its outcome. This paper provides insight into the practical issues and aspects of such activities, which can better shape the future research towards successful applications. The difference between an economically viable design and a design aiming at maximum efficiency is therefore also highlighted.

Table 1: Summary of experimental investigations of micro scale (<10 kW_{el}) biomass-fired ORC power systems

Reference	Th./Net el. output (kW)	Working fluid	Expander technology	Cycle layout	η_{exp}/ η_{net}(%)	Fuel	Note
(Kaczmarczyk, Żywica and Ihnatowicz, 2015)	25/1.5 (gross)	HFE7100	4-stage radial turbine	Heat transfer loop, recuperated	71/6 (gross)	Wood pellets	Own radial turbine prototype and multi-fuel boiler
(Qiu *et al.*, 2012)	47.3/0.9	HFE7000	RVE	Heat transfer loop, recuperated	53/1.4	Wood pellets	Ashwell boiler with added ORC circuit
(Mascuch *et al.*, 2021)	42/2	MM	RVE	Direct heating, non-recuperated	61/4	Wood chips	Attempts for commercialization; own expander and boiler tech.
(Jradi and Riffat, 2014)	9.5/0.5	HFE7100	Scroll	Heat transfer loop, recuperated	74.2/4.2	Wood pellets	Follows up on (Qiu *et al.*, 2012); micro trigeneration system
(Carraro *et al.*, 2020)	28/2.3	R245fa	Scroll	Heat transfer loop, recuperated	57/7.4	Wood pellets	Attempts for commercialization

Previously, the authors developed a 50 kW_{th} 2 kW_e woodchip fired ORC system with a vane expander (Mascuch *et al.*, 2020) which is a result of previous continuous development of the older lab-scale systems summarized in (Mascuch *et al.*, 2017). This system has been modified into a containerized unit with the purpose of commercialization with an experience from the pilot application on-site as described in (Mascuch *et al.*, 2021).

As it turned out, for many prospective applications, this unit did not satisfy the overall cost requirements. Therefore, the system has been re-engineered towards further simplification and partial scale up to just about the double power output with the prospect of reaching the requirements of a wider range of feasible installations. This paper describes the new ORC system with nominal parameters 120 kW_{th} and 6.2 kW_e (net), decisions that led to alternative technical solutions and operating parameters. Finally, economic analysis provides insight into considerations for market-successful ORC microcogeneration systems.

2 ORC UNIT DESIGN

2.1 System layout

The layout of the upscaled system is shown in Figure 1. The previous ORC unit was operated with the heat source temperature around 600°C, obtained by mixing the flue gas from a combustion chamber with a certain portion of a recirculated flue gas. No detrimental effect based on thermal decomposition and subsequent operation issues were observed even at higher temperatures. A certain level of decomposition into reaching a stable chemical equilibrium might still be happening. Still, in the CHP operation regime with condensation around 90°C, its effect on system performance is negligible. The new system is designed with the aim of simplification and therefore recirculation is not implemented. To control the combustion, there are separate primary and secondary combustion air fans.

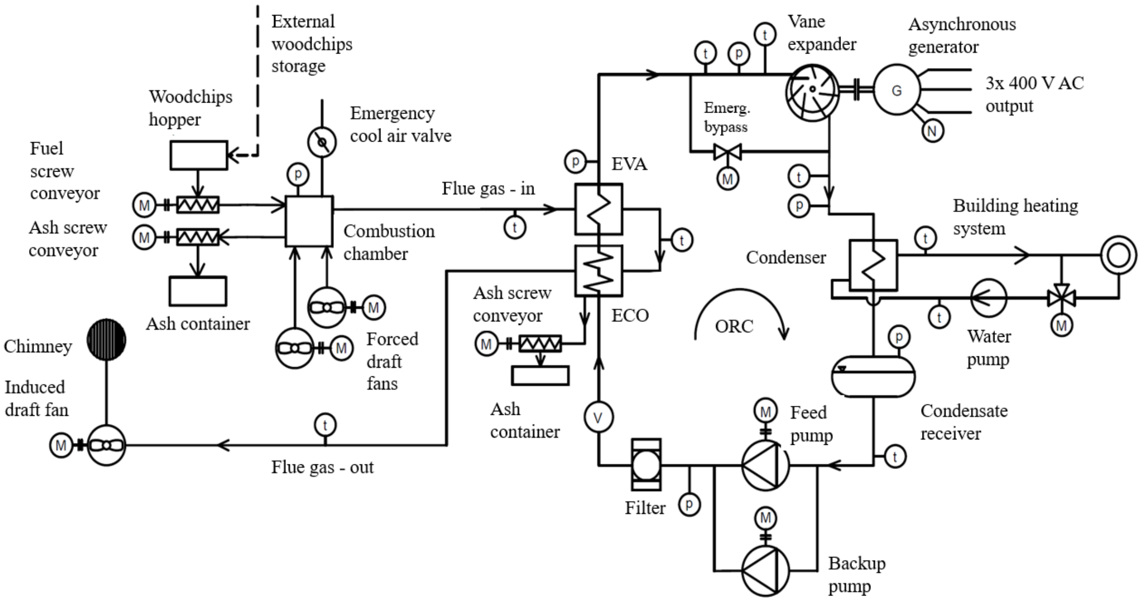

Figure 1: Process flow and instrumentation diagram of the developed CHP ORC unit

Table 2 summarizes a nominal performance of the described unit and, for comparison, a previously developed 50 kW_{th} unit. The whole system has been fitted into shipping contained as a standalone system as seen in Figure 2 along with a model of the applied rotary vane expander, a specific feature of this design, which is further described in the following section. Note the relatively small increase in dimensions and weight between the previous 50 kW_{th} and current 120 kW_{th} systems. Also, the parasitic load is in relative values significantly lower, consuming less than 25% of the gross electrical output compared to more than 40% previously.

2.2 Expander

The system uses an in-house developed rotary vane expander which was chosen in the past due to high cost-effectiveness potential for single piece and small series manufacturing. The design of the expander is shown from two major viewpoints. The first is the overall concept of mechanical design. After previous development, stator, rotor are made of CrMo alloy steel, vanes of stainless steel, and all surfaces are coated in order to reduce friction and increase durability. The rotor is housed in cylinder bearings within the area of the working fluid. The expander is hermetically sealed, and torque is transferred to the asynchronous motor (2-pole, 400 V, 7.5 kW, IE4 efficiency class) in generator mode via magnetic coupling.

Table 2: Overall design/nominal parameters of the current CHP ORC unit

Parameter	50 kW_{th} unit	120 kW_{th} unit	Units
Net electrical power output	2.0	6.2	kW_{el}
Gross electrical power output	3.5	8.2	kW_{el}
Nominal thermal power output	50	120	kW_{th}
Nominal hot water circuit temperatures	80 / 60	80 / 60	°C
Woodchips consumption	14	33.4	$kg.h^{-1}$
Dimensions (L x H x W)	4 x 2.8 x 2.44	6.1 x 3.1 x 2.46	m
Weight	5000	6500	kg

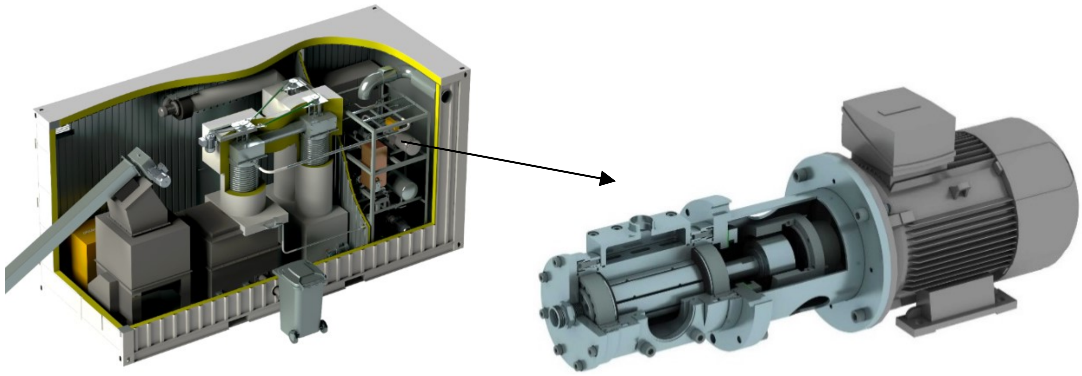

Figure 2: A cross-sectional view into the containerized CHP ORC unit (left) and an assembly of the rotary vane expander, including the magnetic coupling and an asynchronous generator (right)

In the view of the fluid mechanics design, the overall dimensions are a result of an optimization of the computational model of the expander, where the partial models are described in (Vaclav Vodicka *et al.*, 2019). The optimization is performed to maximize the work of the cycle with fixed heat input and is based on a genetic algorithm (GA). The design model calculates the geometrical characteristics of the expander, including the clearances, leakages, vane friction model and a thermodynamic model of the whole machine. Some of the major expander parameters are shown in Table 3, and for comparison, the expander geometry from the previous smaller unit is presented as well. As can be seen from the table, the expander of the new unit shows slightly lower efficiency compared to the previous unit. This is mainly due to the lower built-in expansion ratio of the more powerful expander. As mentioned, the expansion ratio, as well as the other geometric characteristics of the expander, are based on optimization by GA to maximize mechanical power output for a given heat output of the unit. If the more powerful expander were to have the same expansion ratio, its dimensions would have to be increased accordingly, resulting in higher vane friction losses and higher leakage losses. For this reason, GA optimization within provided constraints resulted in the lower expansion ratio as the optimum with the maximum mechanical output.

Table 3: RVE main geometry parameters - comparison of the expanders in 50 kW_{th} and the 120 kW_{th} unit

Rotary vane expander geometry		**50 kW_{th} unit**	**120 kW_{th} unit**
Stator bore	[mm]	78	85
Eccentricity	[mm]	5.5	6
Rotor diameter	[mm]	67	73
Stator length	[mm]	140	204
Vanes thickness	[mm]	1	1
Vanes height	[mm]	21	24
Number of chambers	[-]	8	8
Expansion ratio	[-]	5.1	3.1
Initial chamber volume	[cm^3]	9.7	25.4
Mechanical power output	[kW]	3.4	8.0
Expander isentropic efficiency	[-]	0.606	0.521

2.3 Balance of plant

The electrical system consists of an asynchronous electric generator, motors of feed pumps and air/flue gas fans, but also the fuel or ash conveyors. Other elements with significant electric consumption are instrumentation and control and power electronics. Compared to the previous CHP ORC unit, the current system is not any more equipped with a DC bus, filter and an active front end unit for electricity supply to the grid due to large own electrical power consumption and overall cost. The asynchronous generator is after reaching near-nominal speed connected directly to the grid, and except for the circuit breaker and power factor compensation capacitor, no other power equipment is necessary.

The system for instrumentation and control is based on a standard industrial programmable logic controller (PLC), and common industrial temperature and pressure sensors is in detail described in (Mascuch *et al.*, 2020). In-house developed I&C algorithms allow automatic operation, start-up, shut down, system warnings or emergency features to secure safe operation under any circumstances.

2.4 Auxiliaries

The whole CHP ORC unit is then equipped with additional auxiliary systems to secure its autonomous operation. To list the major auxiliary components, the following overview is provided. At the fuel section of the CHP unit, it is the whole fuel handling system, consisting of the biomass storage, which can hold up to 15 cubic meters of wood chips. This can be filled directly by a truck or with a forklift. From the storage, the biomass is fed automatically to the boiler by screw and hydraulic conveyors. In the combustion chamber and in the flue gas pipeline, the auxiliary components are the electrical ignition system, forced-draft air fans, ash conveyors, automatic mechanical cleaning mechanism to clean the flue gas heat exchangers and finally, the induced draft fan at the chimney inlet. The ORC part of the CHP unit is equipped with a filter to prevent impurities and corrosion products in the working fluid to enter the expander, so that a risk of the coating damage is minimized. Other than that, the expander can be stopped in case of emergency or damage, and the CHP unit still provides heat supply via an emergency bypass at the expander inlet, routing the vapour directly to the condenser. The condensing liquid is then collected in a condensate receiver located directly underneath the flat plate condenser. Hot water circulation pump then belongs to the heating system itself.

3 EXPERIMENTAL PERFORMANCE

Below we present a comparison of the operational parameters of the 6.2 kW_e unit with the previous smaller 2 kW_e unit, as well as a comparison of the implemented rotary vane expanders as a specific feature of our design. The comparison is performed on several thousand hours of experimental data for both units.

3.1 ORC cycle

Nominal cycle parameters are shown and compared in Table 4, based on the experimental measurement during the authorized measurement for certification. In both systems, the gross electrical power output is slightly lower than the design one. The new unit has actually a slightly lower isentropic efficiency of the expander especially due to the lower in-built expansion ratio of the expander (see above) in combination with lower condensing pressure (and thus higher isentropic enthalpy drop) during measurement of the 120 kW_{th} unit.

3.2 Expander

Characteristics of the expander mechanical power output and isentropic efficiency with varied heat input (thus varying the pressure ratio by varying the admission pressure whilst keeping the condensing pressure constant) are shown in Figure 3. The presented values for partial load are obtained from the design model with an optimized RVE geometry for 120 kW thermal input. The model considers a 5% percentage of oil dissolved in the MM charged in the cycle and a 10K subcooling in the condenser, as well as a 10K vapour superheating at the outlet of the flue gas heat exchangers. The comparison between the data from the design model and the experimental measurements is shown in the graph in Figure 3. As can be seen, the model predicts lower expander performance and efficiency in the lower heat rate region. This discrepancy is due to the fact that the model tuning parameters were not chosen adequately. The difference in the experimental results of the expander isentropic efficiency measured during the authorized measurement and the model verification measurement at partial thermal load is also due to the condensing pressure being 5 kPa higher in the latter due to the presence of non-condensable gases in the cycle.

Table 4: Operational parameters of the CHP ORC units measured during authorized measurements

Parameter	**50 kW$_{th}$ unit**	**120 kW$_{th}$ unit**	**Units**
Flue gases			
Evaporator inlet temperature	650	1400*	°C
Evaporator outlet temperature	275	633	°C
Economizers outlet temperature	164	132	°C
Thermal power input to the ORC	46.7	121	kW
ORC			
Expander inlet pressure	553	522	kPa
Expander inlet temperature	182	180	°C
Superheating	10	10	K
Expander outlet pressure	58	46	kPa
Expander outlet temperature	153	158	°C
Condenser pressure	55	37	kPa
Condenser outlet temperature	70	60	°C
MM mass flow rate	0.125	0.3	$kg \cdot s^{-1}$
Heat rejection			
Cooling water inlet temperature	70	58	°C
Cooling water outlet temperature	84	78	°C
Thermal power output	42	113	kW
Auxiliaries			
Expander rotational speed	3026	3034	rpm
Gross electrical power output	3100	7565	W
Net electrical power output	1990	6200	W
Expander isentropic efficiency	61	56	%
Total net CHP efficiency	84	89	%

* Note: Based on flue gas energy balance

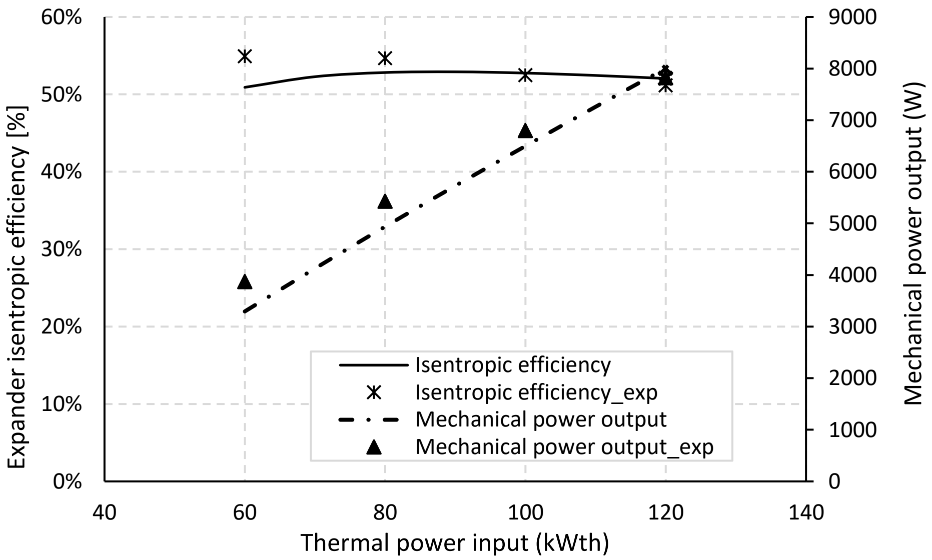

Figure 3: Efficiency characteristic of the rotary vane expander with varied thermal power input – based on the RVE 1D design model (V. Vodicka *et al.*, 2019)

The efficiency curve exhibits a very flat behaviour when operated in the range of between half and full load (60-120 kW$_{th}$). This brings a great advantage for partial load operation of the whole CHP ORC unit since the operation of the expansion machine is usually controlled by and is subordinate to the heat demand. There is however always a drop in cycle efficiency as the expander speed is kept constant, and thus the pressure and cycle efficiency decrease with the decrease of the heat input.

3.3 Overall unit & long term trials

An example of unit operation data during a single winter week is shown in Figure 4. The unit was operated based on the heating system (containing thermal storage tanks) requirement at the University Centre for Energy Efficient Buildings (UCEEB) at CTU with the high load during the day, minimal partial load at night and three shutdowns on Friday and weekend with little to none demand. During the week of operation, the CHP ORC unit produced 350 kWh of electricity supplied to the UCEEB building to power other experimental units within the Centre and 10.6 MWh of heat supplied mainly for the space heating and utility hot water.

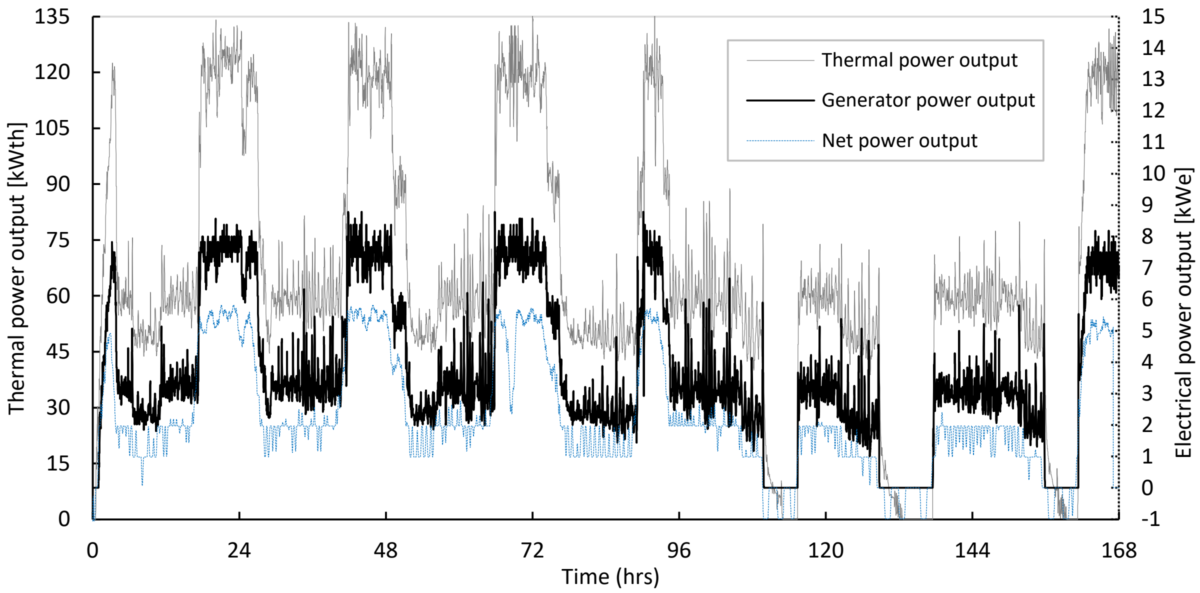

Figure 4: Illustration of operational parameters of the CHP ORC unit over a winter week

Note the difference between the generator output and the net electricity output (averaged over 1 hour periods) after all parasitic loads are subtracted. The main sources of own electrical consumption are the auxiliary components, especially the hydraulic biomass conveyor with the peak power consumption of over 2kW for hydraulic drive and 800W consumed for the electric resistance heating of the hydraulic oil in the winter regime. Other than that, the other auxiliary components such as flue gas fans, a feed pump, screw conveyors, and power electronics are the other large sources of parasitic electrical load. The intermittent operation of some auxiliary systems can be seen well, for example, by the drop in the net electrical output on the 68th hour.

3.4 Legislative requirements for product certification

The biomass-fired CHP units in the EU are required to operate within the efficiency and emissions limit provided by "Ecodesign[1]" regulation. The cycle and unit parameters from this measurement are listed in Table 4, where the requirement for overall 77% seasonal efficiency is met with a significant margin. The imposed emission limits, along with their measured values after recalculation to reference oxygen excess, are shown in Figure 5.

[1] Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to Ecodesign requirements for solid fuel boilers (Text with EEA relevance) *OJ L 193, 21.7.2015*

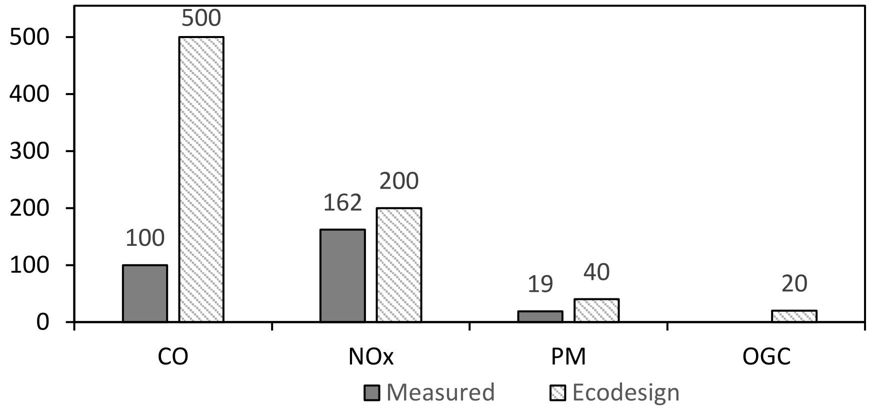

Figure 5: Flue gas emissions measured compared to the Ecodesign limit, ref. O_2 10%

4 ECONOMIC ANALYSIS OF INVESTMENT INTO A BIOMASS-FIRED CHP ORC UNIT

Previous works (Mascuch, Novotny and Tobias, 2018; Mascuch *et al.*, 2021) have shown that economic analysis of CHP systems should be performed with respect to the difference from a reference case regarding both CAPEX and cost of energies during operation. Woodchips fired boiler is a reference case for biomass-fired CHP unit. Table 5 provides a cost breakdown of our 50 kW_{th}, 120 kW_{th} ORC units and a reference 120 kW_{th} biomass boiler.

Table 5: Cost comparison of a biomass boiler and ORC unit for 50 kW_{th} and 120 kW_{th} cases (all costs are indicated in EUR)

TURNKEY DELIVERY COSTS	50 kW_{th}/ 2 kW_{el}	120 kW_{th}/ 6.2 kW_{el}	boiler 120 kW_{th}
Boiler room, flue gas treatment incl.	34 571	38 413	38 413
ORC module	28 870	34 056	0
Heat output, water circuit, pump incl.	1 820	2 083	2 083
Transport, commissioning, etc.	1 931	1 931	1 931
Container	13 914	19 876	19 876
Biomass storage and delivery system	2 124	21 236	21 236
Groundwork	2 054	2 934	2 934
Project preparation	2 510	5 019	5 019
Construction supervision	1 931	1 931	1 931
TOTAL	**89 725**	**127 478**	**93 422**

From the turnkey delivery costs breakdown, it is evident that the overall cost increase in the 120 kW_{th} unit when compared to the 50 kW_{th} unit is approximately 38k EUR. The major increase is, though, not in the price of the ORC module or the biomass boiler (major share of production costs of the combustion chamber and the flue gas heat exchangers is the direct labour cost which stays roughly the same), but the 120 kW_{th} unit is equipped with an external automatic biomass hopper. The ORC module cost is roughly the same thanks to design simplifications, even though for example material cost of primary heat exchanger, newly from stainless steel, increased. This proves, that material costs are not suitable criterion for price determination of micro thermal systems.

The cost difference between the 120 kW_{th} unit and a reference boiler is around 34k EUR and consists of the whole ORC module. The customer would usually consider investing into such biomass-fired CHP ORC in the case of an old boiler replacement, so it is, in fact, this increase in costs between the CHP ORC and the reference boiler which he compares with the annual electricity production and other benefits connected to the CHP unit.

A suitable parameter for a detailed comparison between CHP unit and standalone boiler might be discounted cost of heat instead of the evaluation of only the payback period or the net present value of the investment. But a simple payback of the additional investment into the CHP unit in comparison to the boiler is illustratively demonstrated by a sensitivity analysis with respect to annual system utilization, where the larger system shows a significantly better economic feasibility. Table 6 shows that installation of a biomass-fired CHP ORC unit is commercially beneficial, especially in the case of high annual use of installed thermal power (e.g. sawmill with a hot water timber dryer with a steady heat demand). To provide a simplified economic evaluation, only costs of electricity and cost of fuel consumption difference could be taken into account. The maintenance costs of both solutions are comparable, thus they are not included into the comparison. For the evaluation, biomass price 4.5 EUR/GJ and electricity price for the end-user 110 EUR/MWh were taken into account. A steady net electricity input of 1.5 kW is considered for the 120 kW_{th} boiler and 6.5 kW of net electricity output for the 120 kW_{th} CHP ORC. For the same production of heat, the CHP ORC unit consumes slightly more fuel to cover the direct transformation of heat to electricity and losses of the ORC part of the unit. The most important difference is naturally in the electricity balance.

Table 6: Sensitivity analysis of economic parameters comparing a reference boiler and the presented CHP ORC on the annual system utilization

Annual use of installed thermal power		**h**	**1 000**	**2 500**	**4 000**	**5 500**	**7 000**	**8 500**
HEAT / EL. BALANCE	**Thermal power output**	MWh/y	120	300	480	660	840	1020
	Boiler net electricity consumption	MWh/y	-1.5	-3.8	-6.0	-8.3	-10.5	-12.8
	Boiler fuel consumption	MWh/y	150	375	600	825	1050	1275
	CHP net electricity production	MWh/y	6.5	16.3	26.0	35.8	45.5	55.3
	CHP fuel consumption	MWh/y	158	395	633	870	1107	1344
CHP vs. boiler	**Fuel consumption balance**	MWh/y	8.1	20.3	32.5	44.7	56.9	69.1
	Electricity savings	MWh/y	8.0	20.0	32.0	44.0	56.0	68.0
COST BALANCE	**Cost of additional fuel**	EUR/y	132	329	526	724	921	1 119
	Electricity payment savings	EUR/y	880	2200	3520	4840	6160	7480
	Total savings	EUR/y	748	1871	2994	4116	5239	6361
PAYBACK		y	45.5	18.2	11.4	8.3	6.5	5.4

5 CONCLUSIONS

A previously developed woodchips-fired 50 kW_{th} CHP ORC unit with a net power output of 2 kW_e has been scaled up to 120 kW_{th}/6.2 kW_e in order to achieve a better economy of application. The new system is simplified in aspects as an absence of flue gas recirculation or direct connection of an asynchronous generator to the grid. Even though it achieved slightly lower efficiency (cycle, expander as well as overall CHP production), since the cost of the ORC module changes only slightly with the increased scale, the unit cost and cost of produced heat provide significantly better prospects for feasible applications.

This aspect of finding a market niche for the CHP ORC, scaling it up in order to increase its commercial potential, is discussed within a separate chapter debating the economic aspects of investment into such distributed power system. The turnkey delivery cost breakdown is presented based on experience with deliveries of such presented 120 kW_{th} CHP ORC units. These are also compared with a previous 50 kW_{th} CHP ORC unit and a woodchips boiler for a reference. The economic performance significantly varies with the annual utilization of the thermal power output. This effect is investigated by a sensitivity analysis for this parameter and the overall effect on the economic performance. However, this simple economic analysis might not take into account all important aspects, which might be better revealed in more complex approaches such as discounted cost of heat. From the total net combined heat and power production efficiency standpoint, the larger unit exceeds the former one by five percentage points, reaching 89%, even though the expander performance is slightly poorer with a nominal isentropic efficiency of 56%. However, the economic performance of the upscaled unit excels in comparison with the smaller one. Economic evaluation with a reference 120 kW biomass boiler concludes that an increase of the capital cost of the boiler by one third justifies the investment into the ORC CHP module in many applications.

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