Scaling up a woodchip-fired containerized CHP ORC unit toward commercialization

Jan Spale[1,2], Vaclav Vodicka[1], Zbynek Zeleny[1], Jan Pavlicko[1], Jakub Mascuch[1,2], Vaclav Novotny[1,2]*

[1]Czech Technical University in Prague, University Centre for Energy Efficient Buildings,

Trinecka 1024, Bustehrad, 27343, Czech Republic

[2]Czech Technical University in Prague, Faculty of Mechanical Engineering,

Technicka 4, Praha 6, 16607, Czech Republic

*Vaclav.Novotny@cvut.cz

Published article can be found at: https://doi.org/10.1016/j.renene.2022.08.144

Citation:

Spale J, Vodicka V, Zeleny Z, Pavlicko J, Mascuch J, Novotny V. Scaling up a woodchip-fired containerized CHP ORC unit toward commercialization. Renewable Energy. 2022 Sep 20. doi.org/10.1016/j.renene.2022.08.144

Renewable Energy Journal

Low-quality biomass-fired containerized 120 kWth CHP ORC unit

Jan Spale[1,2], Vaclav Vodicka[1], Zbynek Zeleny[1], Jan Pavlicko[1], Jakub Mascuch[1,2], Vaclav Novotny[1,2]*

[1]Czech Technical University in Prague, University Centre for Energy Efficient Buildings,
Trinecka 1024, Bustehrad, 27343, Czech Republic

[2]Czech Technical University in Prague, Faculty of Mechanical Engineering,
Technicka 4, Praha 6, 16607, Czech Republic

*Vaclav.Novotny@cvut.cz

Abstract

Microcogeneration utilizing Organic Rankine cycle technology has a vast application potential, but commercialization attempts in the past have shown challenges in creating competitive products. The market is large, especially in the smallest size and domestic systems, but so is the competition from standard boilers. This was the case also for previously developed biomass fired 50 kWth 2 kWe Organic Rankine cycle unit intended for larger buildings and small industries. Therefore, a scaled-up 120 kWth and 6.2 kWe unit has been proposed with better commercialization prospects. It is attributed to higher net electrical efficiency (relatively lower parasitic load), certain simplifications and design optimizations possible only at the higher power rating.

This manuscript discusses the process of scaling up, designing, assembling and operation of this system. It includes modifications of previously applied technologies regarding the boiler, rotary vane expander and the overall system configuration. Both units utilize a rotary vane expander as a specific feature of the design. A comparison with the previous smaller unit is performed on several thousand hours of experimental data. The larger unit reaches higher net combined heat and power production efficiency, reaching 89%, even though the expander nominal isentropic efficiency slightly drops to 56%.

Keywords

Microcogeneration; CHP; ORC; Biomass; Rotary vane expander

Highlights

- Cogeneration utilizing ORC from low quality biomass for industrial and larger scale space and hot water heating is an economically feasible solution
- An automatic CHP ORC unit with 120 kW thermal output and 6.2 kW electrical output was developed as a containerized solution and now delivered to the market by a spin off company
- Operational data from a long-term experimental campaign are presented
- Experimental validation of a numerical model for rotary vane expander performance in off-design condition is reported

1 Introduction

Biomass is a prospective renewable and sustainable energy source in many regions of the world, providing potential for a notable share of standalone heating as well as power requirements in combined heat and power (CHP) production. The end-users of solid biomass include residential as well as industrial sectors. [1], [2] In some countries, biomass is even the major renewable resource, such as Lithuania with a recorded value of over 80% in 2017 [3]. Further significant growth of this resource is predicted, especially as it is evaluated as the only renewable energy source with relevant industrial use.

Long-distance transport should, however, be limited, and demand should be met by local supply [2], [4], suggesting a larger number of small decentralized energy systems.

This drives many research projects focusing on biomass use and utilization technologies. The first step is often analysis and classification of biomass resources, regarding composition, origin, but also prospective use [5], [6]. Specific research takes place then for specific technologies and their aspects. A comprehensive review of boiler technologies provided in [7] provides a summary regarding combustion, cleaning or control methods out of nearly a thousand biomass boilers below 200 kW. Flue gas cleaning to fulfil emission limits is essential for safe and sustainable biomass combustion, where a detailed review [8] shows that simple low maintenance technologies such as cyclones have important limitations in comparison to electrostatic precipitators and the design of high removal efficiency for a smaller particle is an uneasy task.

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, biomass 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. [9], [10]

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. [11]

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 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**
[12]	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
[13]	47.3/0.9	HFE7000	RVE	Heat transfer loop, recuperated	53/1.4	Wood pellets	Ashwell boiler with added ORC circuit
[14]	42/2	MM	RVE	Direct heating, non-recuperated	61/4	Wood chips	Attempts for commercialization; own expander and boiler tech.
[15]	9.5/0.5	HFE7100	Scroll	Heat transfer loop, recuperated	74.2/4.2	Wood pellets	Follows up on [13]; micro trigeneration system
[16]	28/2.3	R245fa	Scroll	Heat transfer loop, recuperated	57/7.4	Wood pellets	Attempts for commercialization

Previously, the authors developed a 50 kWth 2 kWe woodchip fired ORC system with a vane expander [17] which is a result of previous continuous development of the older lab-scale systems summarized in [18]. 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 [14].

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 kWth and 6.2 kWe (net), decisions that led to alternative technical solutions and operating parameters. Finally, the 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.

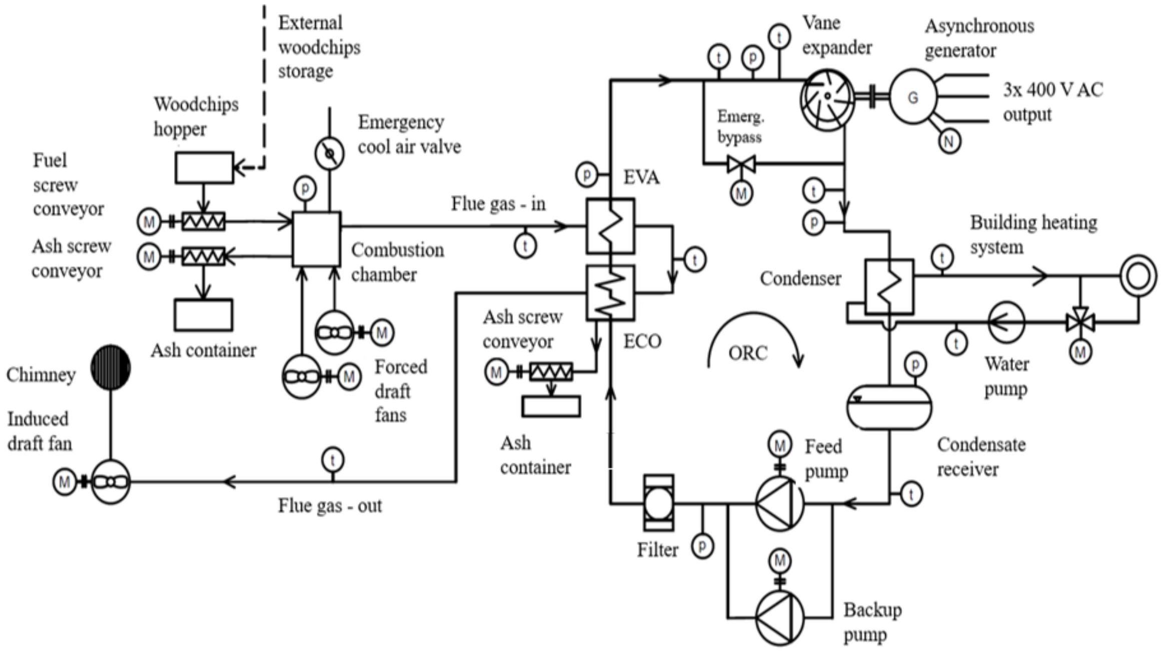

Figure 1: Process flow and instrumentation diagram of the developed CHP ORC unit

Table 2 summarizes a nominal performance of the described unit and, for comparison, a previously developed 50 kWth 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 kWth and current 120 kWth 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.

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

Parameter	50 kWth unit	120 kWth 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

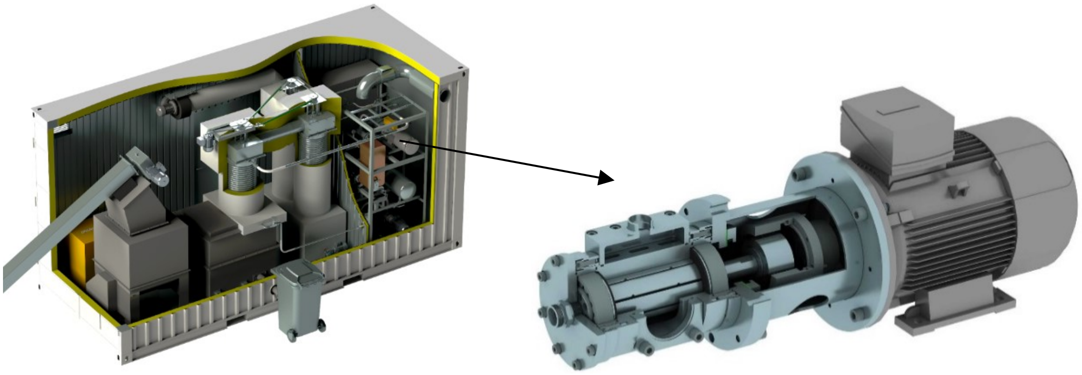

Figure 2: A cross-sectional view into the containerized CHP ORC unit (left) and an assembly of the rotary vane expander, including the magnetic coupling and an asynchronous generator (right)

2.2 Evaporator

The higher capacity of the upscaled unit allows for different design on the evaporator that would not be technically feasible for the smaller 50 kWth unit. It is the higher volumetric flow rate of the flue gas that allows for better heat transfer and thus allows omission of the recirculation. The flue gas flows in an annular space on the outer surface of which is welded spiral pipe with the ORC working fluid. Additional heat transfer is here achieved by radiation of core of the evaporator, defining the inner surface of the annulus. After the evaporator the flue gas goes to the preheater and moves downwards. Preheater has higher surface area than evaporator, partly due to high ratio of specific heat capacity of liquid compared to the heat of evaporation, partly due to lower temperature difference and heat transfer coefficients. Both heat exchangers have employed fly ash cleaning system using rotating chains. The aerodynamic design is further optimized in a way that the fly ash gets deposited before leaving the system through the chimney, so that the particulates emissions are within the legislative threshold.

2.3 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.

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 [19]. 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 kWth and the 120 kWth unit

Rotary vane expander geometry		**50 kWth unit**	**120 kWth 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

2.4 Balance of plant

The electrical system of the unit is depicted in Figure 3. It 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 equipped with a DC bus, filter and an active front end unit for electricity supply to the grid. The reason is in overall cost and mainly in relatively high power consumption, especially when iddle. 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.

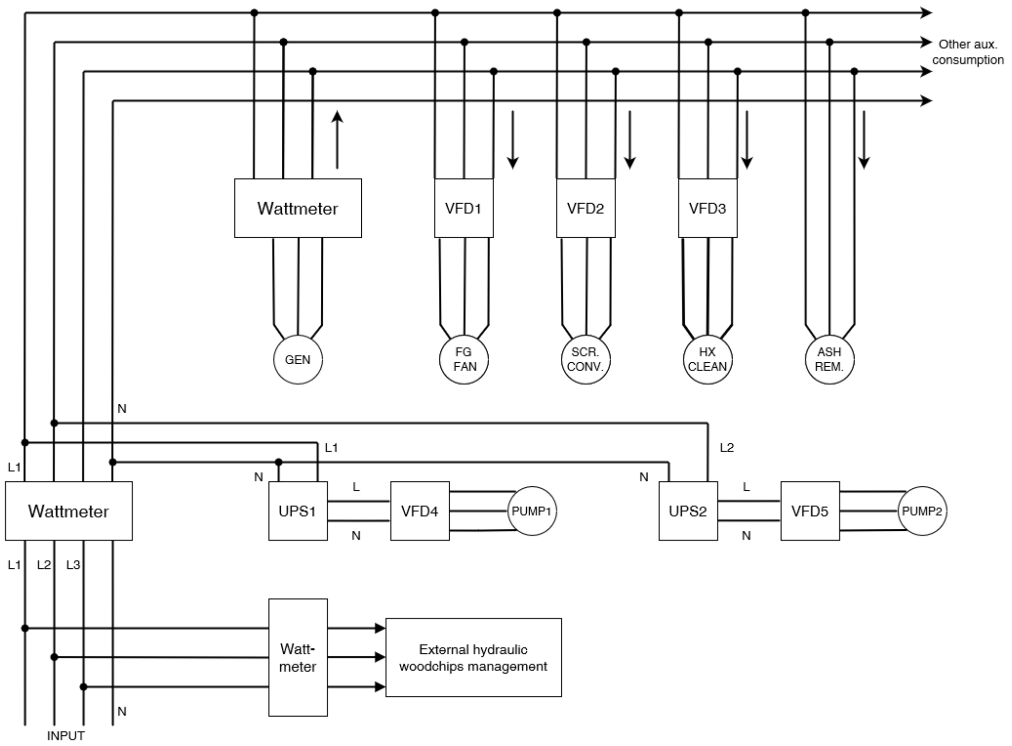

Figure 3: General electrical schematics of the unit

The system for instrumentation and control is based on a standard industrial programmable logic controller (PLC), and industrial temperature and pressure sensors. In-house control algorithms are developed for automatic operation, start-up, shut down, system warnings or emergency features. In order to increase safety of operation, a back-up feed pump is implemented and both pumps are electrically separately backed up.

A list of sensors and their accuracy is provided in Table 4. A special attention has been paid to the combustion control where an oxygen probe is employed in order to provide maximum overall efficiency, low pollutants (CO, NO_x) in steady state as well in transient states.

Table 4: Sensors used in the CHP Unit.

Parameter / sensor type / placement	**Range**	**Accuracy**
Pressure / ceramic, capacitive / low pressure ORC side	(0 - 400) kPa abs.	± 0.35% f.s.
Pressure / ceramic, capacitive / high pressure ORC side	(0 - 1600) kPa abs.	± 0.35% f.s.
Pressure / N/A / combustion chamber	(-100 - 0) Pa rel.	± 5% f.s.
Temperature / thermocouple - type K / flue gas	(-50 - +1100) °C	± max (2.5 °C, 0.0075|t|)
Temperature / Pt100 / ORC, heating water	(-50 - +200) °C	± (0.30 °C + 0.005|t|)
RPM / incremental encoder /generator	(0 - 6000) rpm	± 0.06 rpm @ 3000 rpm
Expander shaft power output / VFD, motor efficiency curve measurements / -	(0.02 – 100) A	± 1% f.s.
Oxygen lambda probe	(0-21) %O2	± 1% f.s.
Calorimeter (Pt100 + ultrasound flow meter)	(0.007 – 12) m^3/h	± 1% f.s.

2.5 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 hydraulic moving floor, 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, moving grate mechanism, automatic mechanical cleaning mechanism to clean the flue gas heat exchangers and finally, the induced draft fan at the chimney inlet. These systems are also designed by the research group, some of them specifically patented such as the air-cooled movable combustion grate, heat exchanger cleaning mechanism and soot formation control.

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 kWe unit with the previous smaller 2 kWe 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. The fuel analysis for the below operational parameters is summarised in Table 5.

Table 5: Fuel analysis of the wood chips burnt in the CHP ORC unit

Wood chips – B1	**Value**	**Units**	**Uncertainty**
Higher heating value HHV	15.93	MJ.kg^{-1}	0.22
Lower heating value LHV	14.35	MJ.kg^{-1}	0.22
Water content W_{tr}	20.03	%	0.01
Ash content A_r	0.18	%	0.02

Note: The fuel analysis was conducted in the as received state by an authorized metrological institution

3.1 ORC cycle

Nominal cycle parameters are shown and compared in Table 6, 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 kWth 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 4. 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 4. 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 5kPa higher in the latter due to the presence of non-condensable gases in the cycle.

;**Table 6**: Operational parameters of the CHP ORC units measured during authorized measurements

Parameter	50 kWth unit	120 kWth 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

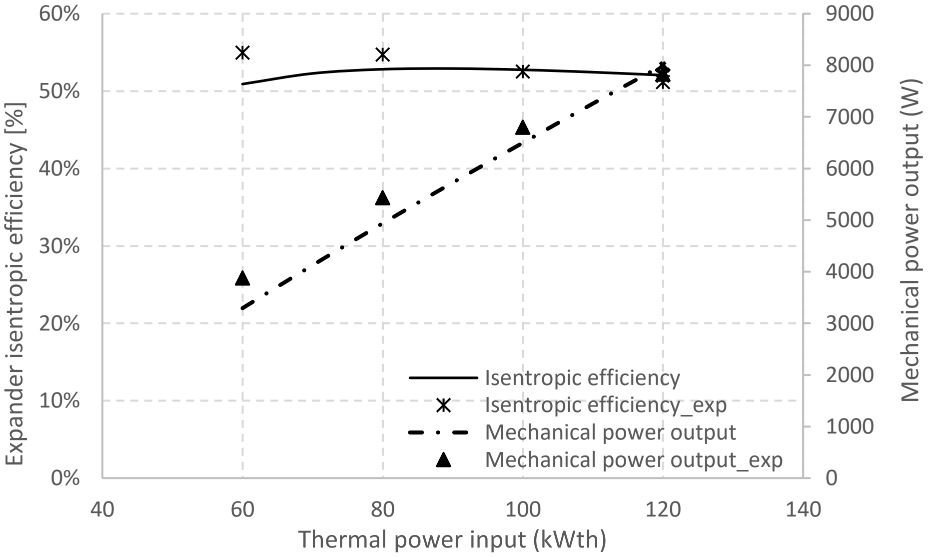

Figure 4: Efficiency characteristic of the rotary vane expander with varied thermal power input – based on the RVE 1D design model [20]

The efficiency curve exhibits a very flat behaviour when operated in the range of between half and full load (60-120 kWth). 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 Operational parameters

An example of unit operation data during a single winter week is shown in Figure 5. 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 38 GJ of heat supplied mainly for the space heating and utility hot water.

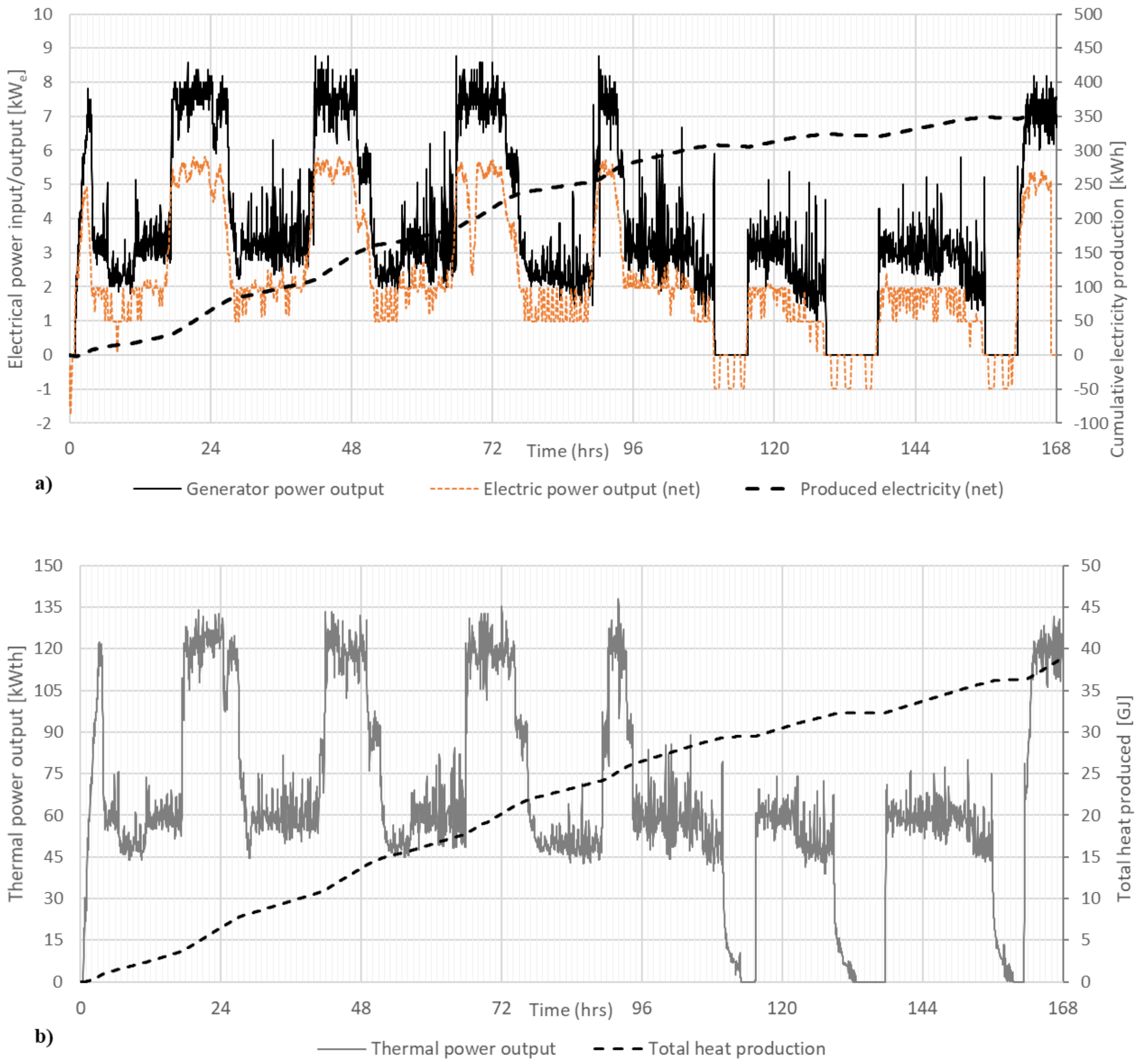

Figure 5: Operational record of the CHP ORC unit over a typical winter week; **a)** electrical power; **b)** thermal power

Note the difference between the generator output and the net electricity output after all parasitic loads are subtracted. The main sources of own electrical consumption are the auxiliary components, especially the hydraulic moving floor 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.

The graph in Figure 6a) shows the course of generator electricity production and the total production (or consumption) of the entire unit. Please note that this is net power, which includes a parasitic load of all equipment (hydraulic moving floor, screw conveyors, draft fans, pumps, electrical ignition system, measurement and control, etc.). When the CHP ORC unit starts from idle mode after a longer period, the electronic ignition system needs to be utilized to ignite the woodchips. This peaks the electrical power consumption up to 2-3 kW for a short period of time as can be seen in Figure 6a) near minute 60. It takes approximately 40 minutes to start the unit from cold state (idle overnight) to the beginning of electricity production, the unit gets into a positive balance of electricity production in another 20 minutes. After the phasing of the generator to the grid, a relatively fast increase of the output follows, but the nominal output is achieved after about 2 hours. At minute 700, the control system of the CHP ORC unit receives a signal from the building, that the demand for hot water has reduced and thus it lowers the power output to half load.

The whole system is rather robust and has large thermal inertia, thus it is beneficial to maintain it in operation overnight in half load condition. The combustion chamber and spiral wound heat exchangers are very heavy as they are designed to be robust and to handle low grade woodchip combustion. The robustness is advantageous at the nominal condition to maintain stable operating condition for the rotary vane expander at the expense of the system’s flexibility.

The second graph, Figure 6b) shows the thermal output of the device and also the cumulative heat production during the same course of operation. The last chart in Figure 6c) shows the course of selected pressures and temperatures over the same time period. The trend of the expander inlet temperature and pressure obviously follows the trend of the thermal power output (input respectively), as the cycle is operated in the sliding pressure regime. Condenser pressure remains more or less constant throughout the operation, determined by the return hot water temperature from the building.

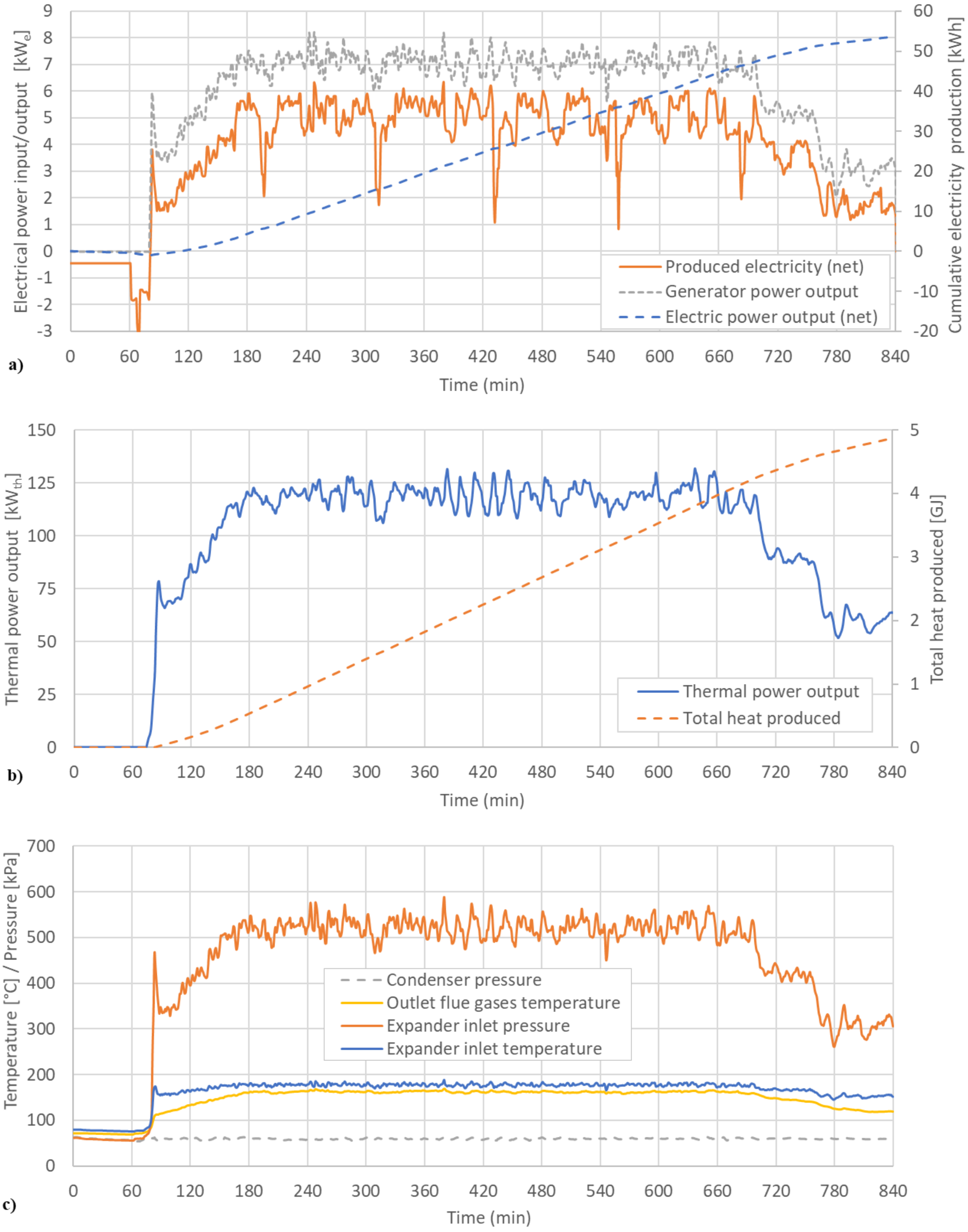

Figure 6: Operational parameters for an illustrative case of a single start-up and nominal operation **a)** electrical power; **b)** thermal power; **c)** temperatures and pressures

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 6, 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 7.

---

[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*

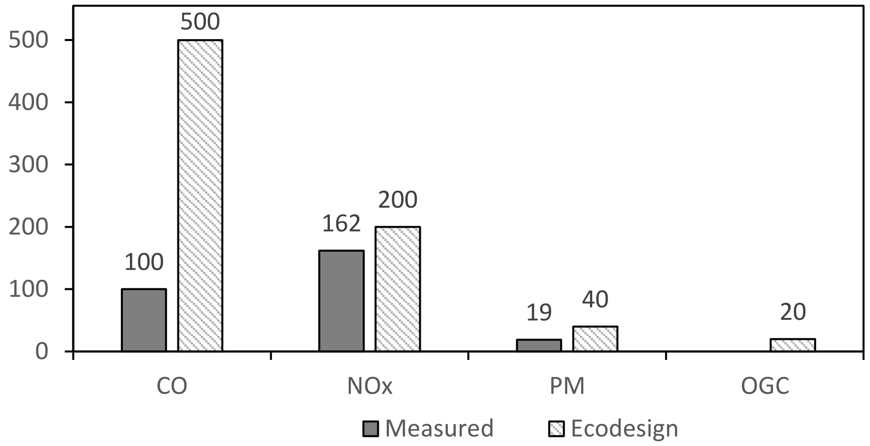

Figure 7: Flue gas emissions measured compared to the Ecodesign limit, ref. O_2 10%

4 Economic parameters

Previous works [14], [21] 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 7 provides a cost breakdown of our 50 kWth, 120 kWth ORC units and a reference 120 kWth biomass boiler.

Table 7: Cost comparison of a biomass boiler and ORC unit for 50 kWth and 120 kWth 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 kWth unit when compared to the 50 kWth 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 kWth 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 kWth 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.

5 Conclusions

A previously developed woodchips-fired 50 kWth CHP ORC unit with a net power output of 2 kWe has been scaled up to 120 kWth/6.2 kWe 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 kWth CHP ORC units. These are also compared with a previous 50 kWth CHP ORC unit and a woodchips boiler for a reference. The economic performance significantly varies with the annual utilization of the thermal power output.

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.

References

[1] A. B. M. Abdul Malek, M. Hasanuzzaman, and N. A. Rahim, “Prospects, progress, challenges and policies for clean power generation from biomass resources,” *Clean Technol. Environ. Policy 2020 226*, vol. 22, no. 6, pp. 1229–1253, Jun. 2020, doi: 10.1007/S10098-020-01873-4.

[2] I. Malico, R. Nepomuceno Pereira, A. C. Gonçalves, and A. M. O. Sousa, “Current status and future perspectives for energy production from solid biomass in the European industry,” *Renew. Sustain. Energy Rev.*, vol. 112, pp. 960–977, Sep. 2019, doi: 10.1016/J.RSER.2019.06.022.

[3] V. Gaigalis and V. Katinas, “Analysis of the renewable energy implementation and prediction prospects in compliance with the EU policy: A case of Lithuania,” *Renew. Energy*, vol. 151, pp. 1016–1027, May 2020, doi: 10.1016/J.RENENE.2019.11.091.

[4] O. Cintas, G. Berndes, O. Englund, and F. Johnsson, “Geospatial supply-demand modeling of lignocellulosic biomass for electricity and biofuels in the European Union,” *Biomass and Bioenergy*, vol. 144, p. 105870, Jan. 2021, doi: 10.1016/J.BIOMBIOE.2020.105870.

[5] G. Cavalaglio *et al.*, “Characterization of Various Biomass Feedstock Suitable for Small-Scale Energy Plants as Preliminary Activity of Biocheaper Project,” *Sustain. 2020, Vol. 12, Page 6678*, vol. 12, no. 16, p. 6678, Aug. 2020, doi: 10.3390/SU12166678.

[6] R. Saidur, E. A. Abdelaziz, A. Demirbas, M. S. Hossain, and S. Mekhilef, “A review on biomass as a fuel for boilers,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2262–2289, Jun. 2011, doi: 10.1016/J.RSER.2011.02.015.

[7] J. L. Míguez, J. C. Morán, E. Granada, and J. Porteiro, “Review of technology in small-scale biomass combustion systems in the European market,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3867–3875, Aug. 2012, doi: 10.1016/J.RSER.2012.03.044.

[8] R. Singh and A. Shukla, “A review on methods of flue gas cleaning from combustion of biomass,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 854–864, Jan. 2014, doi: 10.1016/J.RSER.2013.09.005.

[9] E. Macchi and M. Astolfi, *Organic Rankine Cycle (ORC) Power Systems: Technologies and Applications*. Woodhead Publishing, 2016.

[10] P. Colonna *et al.*, “Organic Rankine Cycle Power Systems: From the Concept to Current Technology, Applications, and an Outlook to the Future,” *J. Eng. Gas Turbines Power*, vol.

137, no. 10, pp. 100801–100819, Oct. 2015.

[11] R. Padinger, S. Aigenbauer, and C. Schmidl, "Best practise report on decentralized biomass fired CHP plants and status of biomass fired small-and micro scale CHP technologies," *IEA Bioenergy*, vol. 32, no. February 2019, 2019.

[12] T. Z. Kaczmarczyk, G. Żywica, and E. Ihnatowicz, "Experimental Investigation of a Radial Microturbine in ORGANIC RANKINE CYCLE SYSTEM WITH HFE7100 AS WORKING FLUID," *Proc. 3rd Int. Semin. ORC Power Syst.*, pp. 1–10, 2015.

[13] G. Qiu, Y. Shao, J. Li, H. Liu, and S. B. Riffat, "Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications," *Fuel*, vol. 96, pp. 374–382, 2012, doi: 10.1016/j.fuel.2012.01.028.

[14] J. Mascuch, V. Novotny, J. Spale, V. Vodicka, and Z. Zeleny, "Experience from set-up and pilot operation of an in-house developed biomass-fired ORC microcogeneration unit," *Renew. Energy*, vol. 165, pp. 251–260, Mar. 2021, doi: 10.1016/j.renene.2020.11.021.

[15] M. Jradi and S. Riffat, "Experimental investigation of a biomass-fuelled micro-scale tri-generation system with an organic Rankine cycle and liquid desiccant cooling unit," *Energy*, vol. 71, pp. 80–93, Jul. 2014, doi: 10.1016/j.energy.2014.04.077.

[16] G. Carraro, V. Bori, A. Lazzaretto, G. Toniato, and P. Danieli, "Experimental investigation of an innovative biomass- fi red micro-ORC system for cogeneration applications," *Renew. Energy*, vol. 161, pp. 1226–1243, 2020, doi: 10.1016/j.renene.2020.07.012.

[17] J. Mascuch, V. Novotny, V. Vodicka, J. Spale, and Z. Zeleny, "Experimental development of a kilowatt-scale biomass fired micro – CHP unit based on ORC with rotary vane expander," *Renew. Energy*, vol. 147, pp. 2882–2895, 2020, doi: 10.1016/j.renene.2018.08.113.

[18] J. Mascuch, V. Novotny, V. Vodicka, and Z. Zeleny, "Towards development of 1-10 kW pilot ORC units operating with hexamethyldisiloxane and using rotary vane expander," *Energy Procedia*, vol. 129, pp. 826–833, 2017, doi: 10.1016/j.egypro.2017.09.196.

[19] V. Vodicka, V. Novotny, Z. Zeleny, J. Mascuch, and C. Republic, "Rotary vane expander - Analysis and prediction of delayed chamber closure," *ORC2019*, no. 5, pp. 1–10, 2019.

[20] V. Vodicka, V. Novotny, Z. Zeleny, J. Mascuch, and M. Kolovratnik, "Theoretical and experimental investigations on the radial and axial leakages within a rotary vane expander," *Energy*, vol. 189, 2019, doi: 10.1016/j.energy.2019.116097.

[21] J. Mascuch, V. Novotny, and M. Tobias, "Economic aspects of micro-cogeneration systems — Insight into investors' approaches," in *2018 Smart City Symposium Prague (SCSP)*, May 2018, pp. 1–5, doi: 10.1109/SCSP.2018.8402654.

Acknowledgement

This work was supported by Technology Agency of the Czech Republic (TACR), project no. TK01020061 Combined heat and power (CHP) ORC unit with thermal output of 120 kW in containerized configuration.