Research of a Biomass Boiler with Stirling Engine Microgeneration Unit

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Abstract – A number of intergovernmental agreements, the most important of which are the Paris Agreement (UN Framework Convention on Climate Change) and the European Green Deal, provide for resource efficiency and the reduction of greenhouse gas and particulate matter (PM_{2.5}, PM₁₀) emissions to 2030 (short-term program to reduce emissions by at least 55 %) and to achieve emissions-neutral production, transport and household activities by 2050. The European Union (EU) has taken the lead in developing and implementing climate change mitigation policies for both industrial and private residential homes in the world through a green course. As an EU country, Latvia has joined both the EU-level climate policy and developed its policy, regulatory documents and action plans for 2021–2030 (Latvia's National Energy and Climate Plan for 2021–2030), climate policy, including a policy aimed at significantly reducing GHG emissions and increasing efficiency in the household sector. Achieving these climate policy goals requires both a change in human habits and more efficient technologies. This article discusses one of the technological solutions that can reduce both greenhouse gas emissions and the release of PM_{2.5} and PM₁₀ from individual heating systems in private homes and small commercial facilities. Calculations of electrical energy production in mCHP mode of the system for household self-consumption based on experiments will be done. The technology involves the production of heat from biomass or other types of renewable energy sources while generating electricity for self-consumption. Conclusions of CHP mode on overall efficiency will be done.

Keywords – Climate policy; cogeneration; efficiency; emissions

kWh _{th}	Kilowatt Hours of Thermal Energy
Wh _{el}	Watt Hours of Electricity
mCHP	Micro Cogeneration
UN	United Nations
GHG	Greenhouse Gases
EU	European Union
RES	Renewable Energy Resources
DH	District Heating
SE	Stirling Engine
NET	Neto Energy Balance Calculating System

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1. INTRODUCTION

Latvia is on its way to achieve the EU climate neutrality goals – by 2050 40 % of the energy produced from renewable energy sources (RES) from total energy consumption (EU average goal for 2030 is 20 %). A significant part of the energy produced by RES is wood biomass (in 2018 62.6 PJ or 80.4 % of the total RES consumption). Energy production from biomass, although less than from fossil energy sources, causes greenhouse gas (GHG) emissions. The main consumers of wood biomass are households (mostly apartment buildings) who using district heating (DH) net and households that are not connected to district heating (mostly private houses). If DH is characterized by an efficient heat production process, then the use of wood biomass in private houses is generally inefficient and has high emissions. The main sources of PM_{2.5} emissions in 2016 are the households and service sector (58.8 %), which widely use biomass combustion plants, the energy production sector (13.2 %) with the extensive use of biomass in district heating boiler houses and cogeneration plants, fuel combustion in the industrial sector (12.5 %) and in the transport sector (4.7 %) [1].

The situation in the household sector is even worse with lower installed power in comparison with industrial sector with the production of electricity in micro-generation plants for their own consumption. In the interests of consumers, Article 30 of the Electricity Market Law has introduced a net electricity billing system for microgenerators, and it has been in force since 1 January 2014 for all households that produce electricity for their own needs from RES. In the middle of 2019, the NET system was used by 384 household consumers and their total installed capacity was 2.12 MW. Since 2012, the Ministry of Economics has issued approximately 600 permits for the introduction of new electricity generation facilities, most of which are microgeneration facilities with a capacity of 0.0035 MW to 0.01 MW. This amount is very small and in a year 2019, 550 microgenerator connections (up to 11.1 kWh) were registered, with total installed electrical capacity 3.23 MW, which is a small part (~0.1 %) of the total installed electrical capacity in Latvia [2].

Latvian government has chosen the main directions for action to reduce emissions in the household sector in 2020–2030:

- Informing and educating the society about the role of RES and the role of each individual in climate change;
- Connection to district heating networks in dense heat consumption areas;
- Development of non-emission RES technologies – solar collectors and PV panels, heat pumps.

To achieve the goals of the EU green course, it will not be enough just to introduce non-emission technologies and transform the industrial sector, it will be important to develop all directions of the economy, including efficient use of RES biomass in the private house sector for heating and electricity production. Especially in countries such as Latvia where forests cover more than 50 % of Latvia's territory, although on average ~25 % of the contribution of economic sectors is made up of wood industry and 10–13 million m³ of wood is felled every year, the growth of wood stock in the forest is still much faster than in economic activity. In 2018, 20 824 tons of wood biomass was produced, of which almost ¾ was exported in the form of energy or cellulose chips and pellets. This amount of wood biomass could be used in the local market and create products with higher added value.

Households consume energy in the form of heat and electricity. There are a total of 817 900 households in Latvia, of which 31.5 % are located in rural areas and 68.5 % in urban areas. 82.5 % of the rural population is provided with decentralized heat supply in sparsely populated rural areas and most of the heat produced by the DH is used in cities (74.3 % of the number of urban households). The total number of households providing individual heat

supply is 356 600, including in rural areas 212 429 indicating that most likely these households in rural areas are private houses (total number of private houses 211 118) [3].

The condition of private house heating equipment is often assessed as very poor, most of it consists of heating equipment (boilers, stoves) that are powered by firewood and are at least 25 years old. Only a small part is high efficiency equipment (e.g., wood gasification boilers). Most of the equipment is old and its efficiency is lower than 60 %, which is also evidenced by the primary heat consumption in the country, of which DH accounts for 26 % and individual heat supply 74 %, although 56.4 % of households are connected to DH.

In more than 90 % of cases, firewood heating is used for private house heating, but it is not only inefficient but also has significant dew emissions. The table below clearly shows the difference of CO₂ emissions between the last years, which proves the development of the described situation with technologies in each of the sectors:

TABLE 1. GHG CO₂ EMISSIONS FROM DH AND HOUSEHOLDS

CO ₂ emitter	CO ₂ emissions in 2010, t	CO ₂ emissions in 2017, t
DH	2277.27	1540.54
Households	1805.37	2049.06

Even more significant are particulate emissions in the household sector, which have an adverse effect on human health. Particulate matter emissions from older heating systems are up to 180 times higher at certain heating modes than newer generation heating systems. If households started to replace obsolete individual heating equipment in rural areas with modern wood gasification plant with integrated electricity microgeneration equipment, it would contribute to Latvia's goals in using RES resources and achieving climate neutrality by 2050, as well as promote rural development and population health.

2. TECHNOLOGY DESCRIPTION

At present, the supply of advanced small and micro scale biomass-based mCHP equipment is limited and not available on free market – only at the laboratory concept or prototype level. A study of available mCHP technologies concludes that only gaseous or liquid fossil fuel-fired plants are commercially available.

One of the technologies powered by solid biomass fuel is the Stirling engine-based mCHP system. Stirling engines are external combustion engines which, in combination with an electric generator and a boiler, form a closed micro-cogeneration system.

Stirling engine-based micro-cogeneration units have several advantages:

- Wide choice of fuel to be used in the combustion process;
- High thermodynamic efficiency;
- Low noise level;
- Relatively long maintenance interval [4].

Stirling engines have a higher fuel to energy generation ratio, so this type of equipment is more suitable for larger dwellings with a higher heat load to meet heat and electricity demand at the same time.

2.1. Working Principles of Stirling Engine

The Stirling engine itself has been known since 1816, but the technology for mCHP is still under development. It has good potential in terms of its ability to achieve high efficiency,

fuel flexibility, low emissions and good performance at part load, unlike internal combustion engines.

The supply of heat energy from external sources allows the use of a wide range of fuels. For example, renewable energy sources such as solar or biomass. Stirling engines have low service and maintenance rates, are quieter and smoother than internal combustion engines [5].

A free-piston Stirling engine (FPSE) is a variant of Stirling engine in which the displacer and power piston are not interlinked by any mechanical crank mechanism. Flexure springs attached to the respective displacer and power piston cyclically stores and releases mechanical energy, analogously to the angular momentum stored in the flywheel of a kinematic Stirling engine. The displacer and power piston resonate in a shared natural frequency, deriving power from an oscillatory pressure variation that exists mainly due to the cyclic heating and cooling of a gaseous working substance [6], schematically shown in Fig. 1.

The Stirling engine mCHP system can be the main power supply in the household, in combination with other home appliances, like solar panels and solar batteries. The possibility of supplying external heat energy allows constant control of the fuel energy source.

Stirling engines are simple in design and, compared to internal combustion engines, do not require a cylinder lubrication process, an ignition system and an intake/exhaust valve system. Those characteristics as mentioned before are crucial if the engines are used in heating systems that have to run continuously throughout the heating season, or, even in some cases, continuously throughout the year. Low vibration and noise levels allow these devices to be placed in residential homes or even in the living spaces themselves. The above characteristics indicate that Stirling engine-based mCHP can be used in households, especially in rural areas, where it is not possible to connect to the DH and solid biomass fuel (firewood) is available locally.

A single-cylinder, free-piston engine that meets the above requirements for maintenance and ease of operation by our consideration to be the most suitable of the Stirling engine types for household use, as shown in Fig. 1 [7].

Fig. 1. Schematic of free piston Stirling engine [7].

Such motors are still not manufactured on an industrial scale, but their design features allow its integration with a power generator in one shell. The single-shell design facilitates integration in to a biomass boiler, creating a household mCHP unit.

3. TASKS OF THE EXPERIMENTAL PART

Experimental test unit was developed and set up to evaluate the application of households self-consumption scale Stirling engine-based mCHP (Fig. 2). Following experimental tasks was set up by researcher group(authors):

1. Assess the impact of the cogeneration regime on the total heat production of the biomass boiler heating installation;
2. To determine the quality of fuel combustion of a heating installation by measuring CO₂ and O₂ emissions in flue gases at the beginning, middle and end of the operation cycle;
3. To determine the changes in the productivity of the Stirling engine mCHP system depending on the firewood quality, moisture level, the amount and fraction of fuel loaded in the boiler furnace;
4. To determine the gasification and combustion chamber temperatures at the stable operation of the system in cogeneration mode.

Fig. 2. Schematic representation of the experimental equipment with the lifting mechanism.

In the experiment, a model system containing a conventional solid biomass wood log heating boiler with 31 kWh nominal thermal power [8], with upper gasification and lower combustion chambers (Fig. 3) and *Microgen Free Piston Stirling Engine* [9] with integrated electric generator (Fig. 4) nominal power of 1050 kW was used.

TABLE 2. BOILER WORKING MODE AND ENERGY INPUT

Exp. No.	Boiler mode	Fuel	Energy Input with fuel, kWh
1.	Heating	Wood logs with 20 % moisture	39.40
2.	Heating	Wood logs with 20 % moisture	55.16
3.	Heating	Wood logs with 20 % moisture	39.40
4.	CHP	Wood logs with 20 % moisture	65.01
5.	CHP	Wood logs with 25 % moisture	59.17
6.	CHP	Wood logs with 16 % moisture	83.06
7.	CHP	Wood logs with 17 % moisture	96.67
8.	CHP	Wood logs with 12 % moisture (50 %), saw dust bulks with 8 % moisture (50 %)	266.69
9.	CHP	Wood logs with 10 % moisture	118.07

Note: Fuel moisture was measured manually with Moisture Meter mentioned in Section 3.1, contend during experiments

Fig. 3. Solid biomass gasification boiler [8].

Fig. 4. Microgen Stirling engine with integrated electric generator [9].

To perform the experiments, an engine lifting mechanism was developed for the unit (Fig. 2). Lifting mechanism ensures that the engine head is fed into the combustion chamber so that the unit works in cogeneration mode also if lowered, allowing the boiler to operate only in heat production mode.

In order to perform the experiments, the equipment was installed in the municipal DH boiler house. Schematics Fig. 5. The DH boiler house was chosen to provide a constant heat demand. This study does not analyse the operation of the system in a real Latvian household and does not consider the impact of household consumption indicators on the operation of the system.

Fig. 5. Drawing of the connection of experimental mCHP equipment with the Heat energy consumer.

3.1. Analytical Equipment Used for Experiments

The following equipment was used for the experiments:

- Flue gas analyser *Testo 340*;
- Data acquisition software with temperature sensors *Stirling Engine Data viewer*;
- IR Thermal camera *InfrecAnalyzer LT*;
- Heat meter *Sontex Supercal 739*;
- Wood moisture analyser *iCcraft*.

4. RESULTS

1. Different fuel moisture and entered mass of firewood was used to detect boiler thermal and summary CHP mode efficiency. To detect cogeneration mode effect to boiler thermal efficiency experiments are performed in thermal and CHP mode using fuel with the same parameters, as described Table 2. Three experiments (1–3, Table 2) were performed only in the heat energy production mode, while the experiments (4–9) were performed in the cogeneration mode.

The calculations of thermal and electrical efficiency were done in each of the experiment. Comparison between input energy (firewood) and measured output of thermal and electrical energy was performed. Results of the experiments are presented in Fig. 6, showing how much energy was entered with fuel (wood) and how much thermal and electrical energy was produced in each of the experiment expressed in kWh. efficiency (%), as well as electricity production is present in each of experimental cases. In addition, it was calculated how much in average thermal and electrical energy experimental unit is able to produce from 1 kg of wood.

Fig. 6. Produced thermal and electrical energy from input energy.

From experiment results presented on Fig. 6, calculations of system thermal and summary (thermal + electrical) efficiency expressed in (%) were calculated Fig. 7.

Fig. 7. Thermal and summary CHP mode efficiency.

Evaluating the results of the experiments (Table 2), no influence of electricity production in CHP mode was found to the thermal productivity of the boiler Fig. 8. Those findings could be possible because of specific construction of the boiler, because part of the heat energy was recovered from Stirling engine cooling circuit, so it gives extra heat collecting surface. Those electricity production figures (Fig. 6) include boiler self-consumption, which is about 180 W [8]. No markable loss of thermal capacity was found in experiments 4–9. The above leads to the conclusion that the operation of the plant in the cogeneration mode increases the overall efficiency of the plant (Fig. 7) compared to the identical boilers [10], [11], which operate only in the heat energy production mode.

Evaluating the emissions from the heating system Fig. 5, measurements of CO₂ and O₂ in flue gases were taken every 15 min during all experiment with flue gas analyser *Testo 340*. Emission measurements were performed as described in methodology [13]. Qualitative combustion process was observed, in stable combustion process from 30–180 min. of the experiment Fig. 8, which complies with the ‘A’ class boiler standards [12].

Fig. 8. Thermal efficiency of the boiler.

- The productivity of the Stirling engine was measured with *Stirling Engine Data Viewer* software, by logging data every 15 min. According to the plan set (Table 2), different types of fuel and moisture content were used in the experiments. Additionally, firewood and sawdust briquette combinations were tested.

Fig. 9. The power of the mCHP electric generator (blue line), depending on the Stirling engine head temperature (red line) from the most representative experiment No. 7.

In the course of the experiment, a correlation was found between the temperature of the Stirling engine head and the electricity produced by the generator in each of the experiments 4–9 (Fig. 6). One of the most representative experiment results are shown in Fig. 9 on experimental minutes 90 and 150. We also found out that electricity production drops down

sharply with relatively smooth temperature drop and then rises up with a little temperature increase. Measurements were taken 13 times, every 15 minutes, fuel was injected only before the boiler was ignited and was not replenished during the experiment, which explains the nature of the slowly dropping temperature curve. The operation of the mCHP device was monitored with analytical equipment and software as used in [14].

3. In order to determine the temperature of the boiler in the stable cogeneration mode during the experiment, temperature measurements were performed by IR Thermal camera *Infrec Analyzer LT*.

Fig. 10. Combustion chamber thermograph and photo images

When measuring the temperature of the combustion chamber with a thermal camera, a direct correlation was found between the temperature of the combustion chamber and the electric power generated by the engine. The best result of the experiment (in the 5th measurement episode of experiment 7) was 590 W_{el}, excluding the self-consumption of the equipment (estimated to vary from 70 to 150 W depending on the operating mode of the equipment), at a combustion chamber temperature of around 600 °C, (Fig. 10) and drove the head temperature 385 °C, captured from *Data Viewer Software* according to [15].

5. DISCUSSIONS

Our research was based on comparison of the literature observation and the data obtained in the practical part of the experiments.

We conclude that it is possible to achieve a higher electrical power for the experimental equipment. Based on the information found in the literature review, the temperature of the combustion chamber in which the Stirling engine head can be inserted is up to 800–900 °C [7]. Considering what has been proved in the experimental part of the study, Fig. 9 measurement shows temperature around 600 °C only, so it can be predicted that the maximum electric power of a particular Stirling engine together with a solid biomass boiler can reach 800–900 W. As described on boiler specification [13] combustion chamber temperature can be reached up to 1200 °C. The observations made in the experimental part of the study indicate that the maximum engine power could also be increased by varying the boiler max coolant temperatures as well as engine cooling system inlet/outlet temperatures. Using higher calorific fuel, such as very dry, less than 10 % moisture, or very dense wood like oak firewood would increase temperature in boiler combust. According to the results of the experimental part, the relative amount of emissions to the produced heat and electricity is lower in comparison with analogous boilers without micro-cogeneration, while “A” class

boilers [9] are certified with the same level of emissions just for heat production only, but with the same amount of emissions we have produced electricity as shown in Fig. 8.

6. CONCLUSIONS

Solid-biomass micro-cogeneration units based on the Stirling engine can be more efficient by part of produced electricity than similar heating units operating only in the heat production mode. From measurements in experimental part of the research based on data expressed on data shown on Fig. 6, we calculated that in average from 1 kg of wood could be produced 2.23 kWh thermal energy and in addition we get 7.84 Wh of electrical energy. The tests dose not showed markable heat energy production difference when unit was working in thermal or CHP mode.

To capture precise efficiency increase more detailed experimental equipment should be designed with options to measure full thermal balance of the system.

Gaseous emissions were measured during number of experiments, we captured that during stable operation mode, using wood with moisture content less than 15 % O₂ content in exhaust gases was in a range 4–5 %, using woods logs with moisture 20 % and more, O₂ content increase above 10 %, what we conclude is low quality combustion process. During experiments CO₂ emission differences between unit working in thermal or CHP mode was not captured.

Electrical energy production from Stirling engine alternator was tightly depending on engine head temperature (Fig. 9). We conclude that to get more precise data of produced electrical energy longer experiments are necessary, while during start and finish phase of the combustion process heat temperature is variating and it gives not full overview of the electricity generating process. Our longest experiment was 235 min. only.

Overall, we conclude that using Stirling engine based mCHP system in households gives GHG emission savings by part of extra produced electrical energy compare to conventional wood log gasification boilers.

ACKNOWLEDGEMENTS

I would like to thank RTU VASSI laboratory for the opportunity to use measuring equipment for the practical part of the research. Special thanks to SIA Balteneco for the opportunity to conduct research in its own boiler house, using its infrastructure. Also, thanks to Microgen LTD for the opportunity to use a micro-cogeneration unit for research and Dainis Seržants for responsiveness and quality work by connecting the research unit to the boiler house infrastructure.

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