Micro and small-scale CHP from biomass (< 300 kWₑ) for distributed energy

Technological development and governmental subsidies that are directed towards environmentally sustainable electricity generation have increased the share of distributed generation in many countries during recent years. Combined production of heat and power is suitable for small-scale applications, and micro and small-scale biomass-fired CHP units are one of the alternatives for distributed generation. This relatively new technology has reached the commercialisation stage and could replace conventional boilers in dwellings and provide both electricity and heating to dwellings concerned.

Description of technology

Micro and small-scale CHP is based on following technology types: internal combustion engines, or diesel and gas engines; external combustion engines that are Stirling engines, organic Rankine cycle engines, steam engines and micro turbines; and additionally, fuel cells.

The last mentioned technology is not dealt in this paper due to technology paper 3: Fuel cells using renewable energy sources – a leap to hydrogen economy.

Diesel and gas engines

Diesel or gas engine system means a standard engine driving an alternator to convert mechanical work produced at the engine shaft into electricity. The heat of exhaust gases, i.e. heat resulting from combustion during power generation, is used for process heat supply or heating purposes: it can be recovered at more than 70% efficiency by cooling at 120°C (gas engine) or 200°C (diesel engine). So, exhaust gases and engine cooling water function as heat sources.

Possible biomass based fuels for diesel and gas engines are biogas including sewage and landfill gas, bio-oils, like pyrolysis oil, and gas from biomass gasification. In fact, there are three main alternatives under R&D for power generation via diesel and gas engine systems based on biomass utilisation: fixed-bed gasifier coupled to diesel/gas engine, pyrolysis oil combustion in diesel engines and, in addition, anaerobic digestion and gas/diesel engine.

Biomass gasification is the latest generation of biomass energy conversion processes and thus, electricity production based on fixed-bed gasifier coupled to diesel or gas engine have been the focus of many R&D
projects in Europe during last few years. Most of the technologies developed or under development are based on slightly modified classical downdraft gasifiers.

**Gasifier biopower system based on gas engine (source: VTT Processes)**

Diesel engine applications for biomass co-generation include production of pyrolysis oil on a large scale and distribution of this bio-oil to small-scale engine power plants. Pyrolysis oil is produced from biomass in a pyrolysis oil production unit. After production the oil-like liquid is transported to diesel power plant and utilised in power generation by diesel engines.

**Fast pyrolysis and diesel engine (Source: VTT Processes)**

Anaerobic digestion is the decomposition of wet and green biomass through bacterial action in the absence of oxygen to produce a mixed gas output of methane and carbon dioxide, i.e. biogas. This biogas can be used in gas/diesel engines for either mechanical power or electricity generation. When using biogas, co-generation has proven energy efficiency. The waste heat generated by the engine is recovered as hot water.

**Micro turbine**

With the concept micro turbine it is generally meant gas turbines the output capacity of which is between 25-250 kW. The gas is burned in external combustion chamber fed in pressurised air from a compressor. The gases produced are introduced into a turbine, where their energy is converted into mechanical energy that drives the alternator. Residual energy produced in the form of a high flow of hot gases can be used in a heat exchanger to obtain process heat, i.e. steam or hot...
water. In order to achieve good electrical efficiency despite low peak temperatures usually a recuperator is used for preheating combustion air with the help of hot turbine exhaust gas.

Both gaseous and liquid fuels can be used in micro turbine as a fuel. The most common fuel used in micro turbine applications is natural gas. What comes to utilisation of biomass based fuels, it is biogas, or sewage and landfill gas, under active R&D. In terms of gasification based systems for biomass CHP technologies, fixed-bed gasifier coupled to micro turbine is the system that is researched most.

**Stirling engines**

Stirling engine is a promising alternative for small-scale electricity production. System is based on a closed cycle, where working gas is alternately compressed in a cold cylinder volume and expanded in a hot cylinder volume. The advantage of the Stirling engine over internal combustion engines is that the heat is not supplied to the cycle by combustion of the fuel inside the cylinder, but transferred from outside through a heat exchanger in the same way as in a steam boiler. Consequently, the combustion system for a Stirling engine can be based on furnace technology, thus reducing combustion related problems typical of solid biomass fuels. The heat input from fuel combustion is transferred to the working gas through a hot heat exchanger at high temperature (680-780°C), and the heat that is not converted into work on the shaft is rejected to the cooling water in a cold heat exchanger at low temperature (25-75°C).

Closed cycle enables the use of working gas that is better suited for heat transfer to and from the cycle than air. Possible working fluids in addition to air are helium, hydrogen and nitrogen.

*Due to external combustion, basically every fuel is possible to utilise in Stirling engine systems. However, Stirling engine is considered as one of the most promising technologies for biomass CHP production. In addition to direct-combustion based systems in Stirling engines also systems with small-scale gasifiers have been under R&D.*

**Organic Rankine cycle engine**

The principle of electricity generation by means of an ORC process corresponds to the conventional Rankine process with the difference that instead of water an organic working medium is used. In the ORC a heat source vaporises organic fluid in a vapouriser, and the vapourised fluid expands in the turbine of a high-speed turbo alternator. The expanded vapour is then condensed in a condenser and pumped back to the pressurised vapouriser. The condenser is cooled by a suitable coolant e.g. in co-generation by the returning heating water. Process is suitable for the electricity production from solid, liquid or gaseous fuels, as well as from waste heat.
Steam turbine and engine

Steam turbines and engines are the most common technologies used in co-generation. Generally, when considering plants with the output under 1 MW, using steam engine is better alternative in terms of cost-effectiveness than steam turbine. The steam engine can produce power from 20 kW, which allows a decentralised application for lower output, and the process itself corresponds to a steam turbine cycle in which the turbine is replaced by a steam engine.

In a steam engine system, where gasifier or direct combustion is combined with steam engine, mechanical energy is produced by the expansion of high-pressure steam, and the heat is recovered at the exit of the engine. Exhaust gas resulting from combustion passes through a boiler in which steam is generated. The steam flows into the steam engine where by expansion it is performing mechanical work that is later converted into electrical energy in the generator. After this, steam passes into the condenser where incidental condensation heat can be used as district or process heat. The water is brought to operating pressure by a feed water pump and is then fed to the boiler, thus closing the cycle.

Applications

All of presented minor CHP technologies are meant to use for decentralised power and heat supply of output upward from around 10 kW. Examples of applications are housing estates, industry processes (especially drying processes), hospitals and sewage plants (utilisation of sewage gas). Applications for micro turbines also include steam generation in small boiler plants, high temperature water networks (over 100°C) laundries and local heat networks. In the figure below there is presented an overview of the typical technological characteristics for small-scale biomass CHP technologies.
Typical technological characteristics for production of small scale CHP (Source: Climtech programme, VTT)

<table>
<thead>
<tr>
<th></th>
<th>Diesel/gas engine</th>
<th>Micro turbine</th>
<th>Stirling engine</th>
<th>ORC</th>
<th>Steam engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity range (kW_e)</td>
<td>15-10000</td>
<td>25-250</td>
<td>10-150</td>
<td>200-1500</td>
<td>20-1000</td>
</tr>
<tr>
<td>Electrical efficiency (%)</td>
<td>30-38</td>
<td>15-35</td>
<td>15-35</td>
<td>10-20</td>
<td>15-35</td>
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<tr>
<td>Thermal efficiency (%)</td>
<td>45-50</td>
<td>50-60</td>
<td>50-60</td>
<td>70-85</td>
<td>40-70</td>
</tr>
<tr>
<td>Overall efficiency (%)</td>
<td>75-85</td>
<td>75-85</td>
<td>75-85</td>
<td>85-95</td>
<td>75-85</td>
</tr>
<tr>
<td>Heat production (°C)</td>
<td>85-100</td>
<td>85-100, steam</td>
<td>60-80</td>
<td>80-100</td>
<td>steam</td>
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<tr>
<td>Lifetime (h)</td>
<td>?</td>
<td>50000-75000</td>
<td>50000-60000</td>
<td>?</td>
<td>&gt; 50000</td>
</tr>
</tbody>
</table>

Present level of market penetration

Diesel and gas engines are internal combustion engines that are very well established and therefore already on the market, with around 8000 installed in total in the EU. The ones employing biomass based fuels are few, only 1% of all biomass CHP technologies in operation.

The breakthrough of the micro turbine has not yet been achieved in Europe. However, in the USA they are often used and have therefore already reached high technological maturity. Micro turbine systems are now at demonstration stage to market maturity and they are expected to be commercially available within 8 years. The share of micro turbines utilising biofuels is, similarly to internal combustion engines, only 1% of all biomass CHP technologies in operation.

CHP plants with Stirling engines are close to market maturity. At the moment they are at pilot stage of development. Intensive research is amongst others done at the research institute Joanneum Research in Graz and Technical University of Denmark, where they are concentrating on tests with a biomass firing equipment. 3% of all operational biomass fired cogeneration plants are based on Stirling engine technology.

In electricity generation ORC technology is still relatively new and is on the point of achieving a breakthrough. This process has attained a high level of development and demonstration units are already in operation. In fact, according to study carried out in spring 2003, there were nine biomass-fired ORC plants that had came into operation in Germany, Austria and Switzerland between 1998 and 2002, and a further eleven plants were under construction and in addition, several at the planning stage.

Steam engines represent the most common technology in the area of small-scale biomass co-generation, and yet it is the only alternative for small-scale electricity production from biomass that can be considered to be fully commercially available. However, in the capacity range below 300 kW_e the technology is not largely proven.

In Finland there are some biomass CHP applications based on diesel/gas engine technology. First operational micro turbine manufactured by Capstone Corporation of USA was installed in October 2003 at Stora Enso Oyj Imatra Mills: the output power of the turbine is 30 kW and it utilises the landfill gas. Stirling engines are the focus of many R&D organisations, mainly Finnish universities in which the engines are used for teaching purposes, similarly to ORC technology, which has been under R&D since the 1980’s. At the moment there are no Stirling or ORC units in “real utilisation” in Finland. What comes to biomass-fired steam turbines, or rather steam engines in the output range under 300 kW_e, there are no operational units.

[Contribution from partners]

The main actors and stakeholders in the EU

The biggest engine developers and manufacturers in Finland are ABB, Wärtsilä and Sisu-diesel.

In terms of micro turbine systems, it is Greenenvironment that provides advanced technologies and solutions for biogas utilisation and acts as a Finnish pioneer in the field of utilising micro turbine technology. Greenenvironment and Capstone Turbine Corporation of USA signed co-operation agreement in 2002, and so Greenenvironment is an authorised sales
and service business partner of Capstone Turbine Corporation in Finland.

There are quite many Stirling engine manufacturers, and to mention a few: WhisperTech of New Zealand, Microgen Energy of UK, Solo of Germany, Enatec of The Netherlands and Sigma of Norway. In Finland, there are no product manufacturers, but organisations active in the field of R&D are Helsinki University of Technology, University of Jyväskylä and Vaasa Polytechnic. As mentioned earlier, active Stirling R&D is carried out at Joanneum Research in Graz and Technical University of Denmark.

What comes to ORC technology in Finland, the technology development is concentrated on high-speed technology with high efficiency (power to heat ratio 0.35). Finnish actors focused on ORC R&D are Lappeenranta University of Technology and YTI Research Center co-operating with Tri-O-Gen B.V. of The Netherlands.

And finally about steam turbines and engines: Wärtsilä BioPower provides biomass-fired power plants, which are based on steam turbine cycle and have the output capacity between 1.0-3.5 MW_e. Units with the capacity under 1 MW_e were tried in operation, but they proved non-functional.

[Contribution from partners]

Assessment of main future market possibilities

The method by which micro CHP, i.e. units with output under 10 kW_e, could enter the market is as a direct replacement for gas boilers in hydronic heating systems, and it is assumed that there are potentially large markets for micro CHP units on the dwelling sector. The countries with the greatest market potential are Germany, France, UK and The Netherlands, as these are countries having greatest proportion of total dwelling stock with central heating systems. What comes to units between 10 and 300 kW, it is the replacement of heating plant in heat only systems that provides the potential market. In this case, Denmark, Finland, Sweden, Austria and Germany could offer the biggest market potential having the greatest proportion of dwellings – around 50% – linked to a district-heating scheme.

Small Stirling engines are supposed to be the most likely to have the highest quantity of sales, cause they have the lowest marginal costs, shortest payback periods and can be utilised efficiently in most dwellings, from apartments to houses.

ORC process is also an economically and technologically interesting solution for small-scale applications. In Finland, the most promising end users for ORC power plants are sawmills and small district heating plants of less than 10 MW_th.

Research and development gaps

Technologies for decentralised biomass CHP plants must be robust and highly available and in addition, they must be designed to run in unmanned operation. This means, a high level of process control and process automation is necessary. Another important factor concerning all of the technologies presented is that they must have good partial load behaviour and the ability to handle quick load changes.

Another issues requiring R&D resources are integration with the electricity distribution network and the home energy system. In particular, network connection standards are at the moment being developed at EU level and in the UK to facilitate the simple, safe and cost-effective connection of small and micro scale CHP units.

In the area of utilising gas and diesel engines in power generation, especially anaerobic digestion applications require further R&D, cause there is a great demand to develop and implement methods to treat different industrial wastes and by-products safely.

In the case of micro turbines, there is need for additional development and testing on the turbine combustion system to expand the acceptable range of gas fuel caloric values and compositions.

Problems concerning utilisation of biomass fuels in connection with Stirling engine are concentrated on transferring the heat from the combustion of the fuel into the working gas. The temperature must be high in order to obtain an acceptable specific power output and efficiency. In addition, the heat exchanger must be designed so that, problems with fouling are minimised.

Examples of existing projects

The first biomass heating plant with a CHP cycle and Stirling engine base has been completed and will be activated in Oberlech, Austria. Plant was developed by Austrian Mawera Holzfeuerrungsanlagen.

Cost-effective application possibilities

Investigating new application possibilities

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References


Technology providers

Diesel and gas engines
ABB Oy, http://www.abb.com
Wärtsilä Biopower, http://www.wartsila.com
Sisu Diesel, http://www.sisudiesel.com

Micro turbines
Capstone Turbine Corporation of USA, http://www.microturbine.com
Greenvironment, http://www.greenvironment.fi

Stirling engines
WhisperTech, http://www.whispertech.co.nz
Solo of Germany, http://www.stirling-engine.de
Enatec of The Netherlands, http://www.enatec.com
Sigma of Norway, http://www.stirlingengines.org.uk
Joanneum Research, http://www.joanneum.ac.at
Technical University of Denmark, http://www.dtu.dk

ORC
Lappeenranta University of Technology, http://www.lut.fi
Tri-O-Gen B.V. of The Netherlands, http://www.triogen.nl

YTI Research Center, http://www.mikkeliamk.fi
Steam turbines and engines

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Produced

OPET Finland, VTT, 11/2003