SmartCHP

Cogenerating a renewable future

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Acknowledgments

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The views expressed in this booklet are those of the consortium and cannot be attributed in any way to the European Commission. Written and edited by James Ling and Piero Valmassoi of Greenovate! Europe, with contributions from consortium partners. Graphic design by Formas do Possivel.

Contents

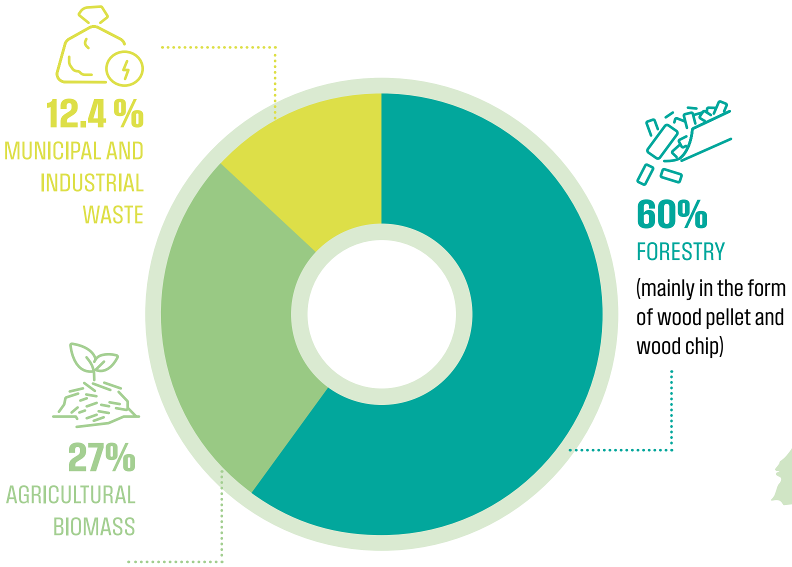
The role of small-scale bio-CHP

Bioenergy is a form of renewable energy generated by burning biomass fuel. Biomass fuels come from organic material such as harvest residues, purpose-grown crops and organic waste. The climate impact of bioenergy varies considerably depending on where biomass feedstocks come from and how they are grown.

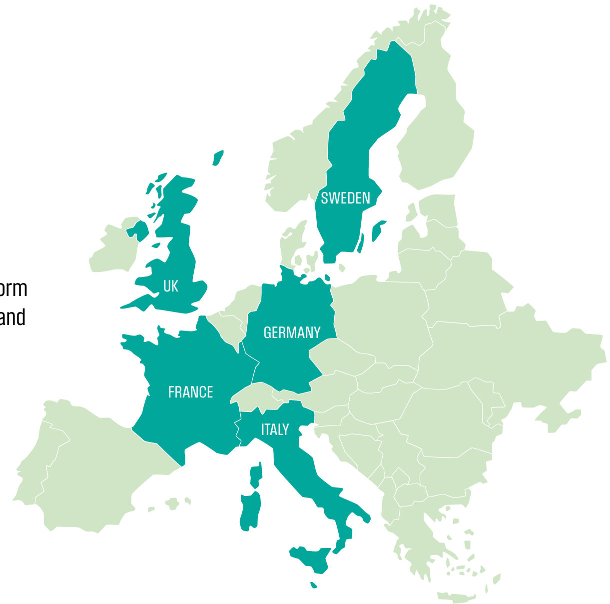
Bioenergy

represents the most used renewable energy in Europe and globally, accounting respectively for 60% and 55% of renewable energy shares.

EUROPE
main source



EUROPE
top five consumers



The key condition for bioenergy development is the availability of reliable, affordable, and sustainable biomass, along all the steps of the value chain: growing and harvesting of feedstock, processing, conversion and distribution of bioenergy to final energy use. The environmental performance of a bioenergy source depends on its specific characteristics of those steps. If well managed, bioenergy pathways can deliver significant GHG savings, whilst ensuring food security and preserving ecosystems.

Bioenergy is an important pillar of decarbonisation in the energy transition as a near zero-emission fuel and thanks to its role as a flexible producer, providing the possibility of balancing the power system and allowing for higher shares of variable renewable energy sources, such as solar and wind, in the electricity grid. One of the most relevant applications of biomass for heating and cooling purposes is cogeneration, also known as CHP (combined heat and power): the simultaneous production of heat and electricity from a single energy source.

CHP is the most efficient form of power generation as surplus thermal energy is recovered and used for heating. It can also change the ratio of electricity and heat produced to suit demand. Currently though, around 80% of cogeneration plants use natural gas and heavy fuel oils as their primary energy source. In this context, **renewable biomass as sustainable energy source for cogeneration plants has a significant potential to replace fossil fuels**. This is because running CHP on biomass is increasingly common and proved to have a high commercial potential for a diverse range of commercial and tertiary sectors applications, such as: hotels, office buildings, retail, hospitals, educational buildings, and greenhouses.

Biomass supply chain assessment

Selecting the right biomass feedstock strategy is key to the ensure smooth operation of the SmartCHP plant. Long-term security of supply, cost and availability are all crucial for sustainable biomass choices.

Capax Biobased Development assessed the supply chain and selected the most suitable biomass for the SmartCHP system. They first researched the availability of feedstocks within four feedstock categories: agriculture, forestry, organic waste residues and dedicated lignocellulosic biomass crops. One feedstock choice was made per category for a deeper supply chain assessment - from harvest to plant. The concept of 'virtual plant locations' was used to conduct tangible analysis based on hypothetical plants in Sweden, Romania, Greece and Croatia. Availability, price, logistics, suitability and sustainability were all analysed.

The results showed that the project can expect corn stover to have the lowest yield of FPBO, while softwood should return the highest yield. Miscanthus and olive kernel wood is expected to have an average yield. **The data concluded that the four chosen feedstocks fulfil EU sustainability criteria, with GHG emission savings far above those required by the EU targets.**

Discover the results

Biomass supply chain assessment (report)

Sustainability assessment (report)

Choosing the right biomass feedstock strategy (webinar)

As a feedstock specialist, it is exciting to see the sustainable evolution of cogeneration plants, where the shift is happening from unsustainable to sustainable feedstock choices. We were pleased to share our expertise within the field and be part of a project that contributes to climate mitigation.

Amanda Kozlo, Capax Biobased Development

Converting biomass residue streams into a good quality FPBO is a decisive step to allow widespread utilisation of these residues in a variety of applications, including flexible heat and power generation through SmartCHP, production of advanced biofuels for difficult to decarbonise sectors and to provide a renewable carbon source for the production of biobased chemicals and materials.

Evert Leijenhorst, BTG Biomass Technology Group

Production of Fast Pyrolysis Bio Oil

Fast Pyrolysis Bio Oil (FPBO) can be produced from a variety of lignocellulosic biomass materials. Commercial scale production of FPBO currently utilises only woody residue streams, as they tend to deliver high FPBO yields and a good product quality. The use of agricultural residues (e.g. corn stover), organic waste streams (e.g. olive kernels) and dedicated energy crops (e.g. miscanthus) provide the **opportunity to widen the feedstock basis and implement FPBO production at different regions throughout the EU and worldwide**.

In the SmartCHP project, research and development work has been performed by BTG aiming to improve the conversion efficiencies for non-woody biomass materials. Dedicated quality control measures (moisture, solid & ash removal) of the FPBO ensured that the product derived from residual biomass materials meets the quality requirements for use in the SmartCHP system. The impact of the different feedstocks on standardisation, REACH registration and HSE (Health, Safety and Environment) were also investigated.

All feedstocks supplied by Capax Biobased Development were converted into FPBO with a suitable quality for the SmartCHP system. For the olive kernel and corn stover derived FPBO, moisture removal was required to obtain a homogeneous liquid. The miscanthus performed very well and a good product was obtained without further conditioning.

Discover the results

Production of FPBO from selected feedstocks (report)

Ignition and combustion of FPBO

The SmartCHP system aims to fuel an engine with fast pyrolysis bio-oil (FPBO) for power generation, however the properties of FPBO make its application in engines very challenging. The Power and Flow Group in the Department of Mechanical Engineering at the Eindhoven University of Technology (TU/e) researched this topic within the project.

Firstly the team carried out fundamental FPBO spray combustion research in their lab. They observed poor atomization of FPBO sprays, and **found that combustion could be improved by either increasing the injection pressure of by adding a small amount of ethanol**. These results were used to improve the design of the fuel injection system in the SmartCHP engine.

TU/e then analysed the performance of FPBO during engine testing at BTG, reporting combustion and emission characteristics. This provides key insights for improving engine efficiency and reducing pollutant emissions.

Discover the results

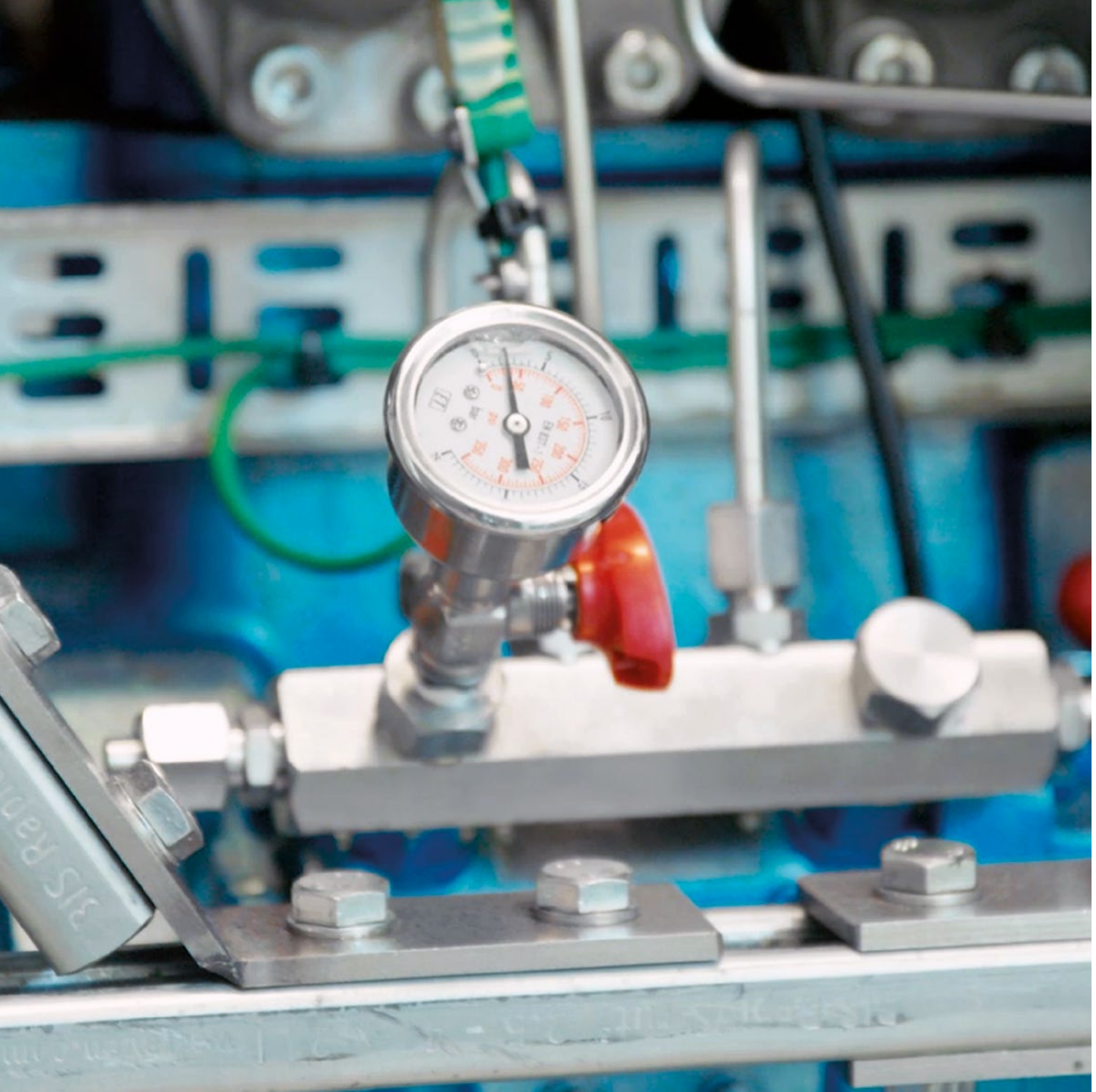
Spray combustion of fast-pyrolysis bio-oils under engine-like conditions (journal article)

Ignition and Combustion Characteristics of N-Butanol and FPBO/N-Butanol Blends With Addition of Ignition Improver (journal article)

Eindhoven University of Technology - Zero Emission Lab (video)

The close combination of scientific research and engineering application makes this project special. I'm exciting to witness how my research achievements push forward the application of FPBO in combined heat and power systems.

Yu Wang, Eindhoven University of Technology (TU/e)



Boiler performance using FPBO

The SmartCHP system combines a FPBO fuelled engine and flue gas boiler to produce electricity and heat at a high efficiency over the whole load range. Within the project a new burner-boiler system was developed by OWI Science for Fuels that can be operated with pure FPBO or a mixture with up to 20% ethanol and flue gas from the engine with an oxygen content between 5% and 18%.

The combustion of FPBO in flue gas was extensively studied. A 17kW and 100kW burner were developed and experimentally investigated under different boundary conditions a in water-cooled combustion chamber (boiler). Results showed that the combustion of FPBO in flue gas and the quick start of the burner even at low flue gas temperatures down to a certain O_2-limit (15% O_2 at low flue gas temperatures) works very well.

The flame speed decreases sharply with decreasing O_2 contents. Low flame speeds make it difficult to stabilise the flame in the burner. The flue gas temperatures of up to 732K limit the flame speed drop and will help to stabilise the flame at lower oxygen contents.

The flue gas temperatures of up to

732K LIMIT THE FLAME SPEED DROP
HELP TO STABILISE THE FLAME AT LOWER OXYGEN CONTENTS

Based on these results, a boiler concept was developed and integrated in to the SmartCHP prototype.

Discover the results

Boiler performance
using FPBO for a SmartCHP system
(report)

Smart control unit

SmartCHP is a highly a flexible cogeneration unit capable of adjusting its power-to-heat ratio according to demand. Nevertheless, integrating the unit into a larger energy system, characterised by various renewable energy sources, and dynamically changing demand presents a challenge. To address these complexities, and ensure the optimal operation of the plant, the team at the Danish Technical University (DTU) developed a smart control unit.

The first step saw the development of dynamic models for key plant components, including modified diesel engines, flue gas burners, and selective catalytic reduction systems. These models were integrated into a comprehensive system model, akin to a digital twin, which made it possible to simulate and analyse the plant's behaviour under various conditions. Subsequently, **control strategies for the SmartCHP unit were developed and optimised.** To achieve this, extensive experiments and simulations using the digital twin were conducted, helping to fine-tune the control algorithms.

The result is a verified system model of the complete plant prototype, implemented in Python (a high-level programming language), which can accommodate future modifications of cogeneration concepts. **The control unit helps to exploit the remarkable flexibility of SmartCHP, while ensuring it operates at the utmost efficiency; meeting energy demands while simultaneously minimising pollutant emissions.**

Discover the results

Predictive Dynamic Model of a Smart Cogeneration Plant Fuelled with Fast-Pyrolysis Bio-Oil
(journal article)

Model-based fault diagnosis of selective catalytic reduction for a smart cogeneration plant running on fast pyrolysis bio-oil
(journal article)

Nonlinear control of a selective catalytic reduction unit for a bio-fueled cogeneration plant
(journal article)

I'm proud to have been part of the SmartCHP project, which excels in biomass-based cogeneration, addressing the challenges of intermittent energy supply and changing demand. This not only has a positive impact on our economy and environment but also exemplifies our commitment to pioneering cleaner, more sustainable energy technologies for the future.

Seyed Mohammad Asadzadeh, DTU

SmartCHP prototype

The SmartCHP prototype has been built at the premises of BTG Biomass Technology Group in Enschede, the Netherlands.

More information about the prototype design and performance is described on the next page.

SmartCHP prototype

During the first months of the project, the sizing of various components (boiler, flue gas treatment) as well as the control mechanism were agreed upon between the relevant project partners. The goal was to construct the SmartCHP prototype based on the capacity of the 50 kWe Abato genset. **Frequent iteration between the component performance test results and prototype design allowed the construction of the first ever SmartCHP prototype.** Two large hot water storage tanks were included in the system as well to optimally utilise the heat generated by the prototype. These heat buffers also provide the necessary flexibility to test the prototype during warm days.

The prototype was used to experimentally validate the SmartCHP concept. The main finding of the experimental work is that the operational window of the prototype turned out to be smaller than anticipated. In the current system the capacity of the boiler could only be varied in a relatively small range, due to limitations in fuel supply capacity and the minimum oxygen content required for combustion. A re-design of the fuel injection method as well as the option to feed additional air into the flue gas boiler could increase this operational window. However, some alternative CHP solutions were considered during the project which may provide the desired flexibility at similar or better efficiencies in a system with lower complexity. The combination of the engine with a heat pump for example could (theoretically) increase the overall efficiency of the system beyond 100%, with the additional benefit that the system does not burden the electricity grid in time of high heat demand (winter).

The 50 kWe prototype, in combination with the design-book prepared for a 250 kWe SmartCHP unit, and the evaluation of various alternative options, provide valuable information and guidance for future development activities. **Follow up work will ensure an efficient and flexible CHP system, suitable for small to medium scale heat and power generation, will be developed based on the FPBO fired internal combustion engine. This allows highly efficient usage of biomass residues for heat and power generation.**

Discover the results

Performance testing of the integrated SmartCHP prototype (report)

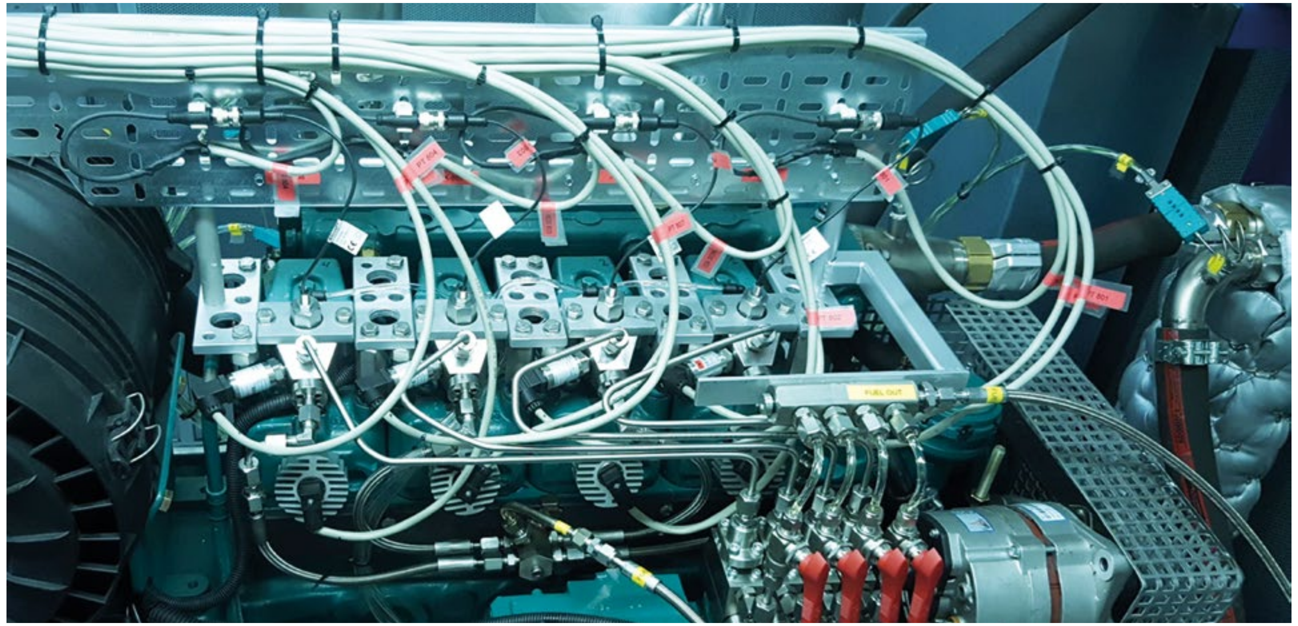
Flue gas treatment

Minimising particulate emissions in line with current and future legal requirements will be vital for the uptake of the SmartCHP system.

During the project, Tehag was responsible for developing a gas cleaning system, which was subjected to 100 hours of testing. The developed catalyst shows good functionality with the pyrolysis oil flue gas.

The catalytic flue gas treatment successfully minimised carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter, achieving the most stringent of emission requirements. Based on these results a treatment unit was developed and integrated into the SmartCHP prototype.

100 hours OF TESTING



Engine operating on FPBO

Combustion of FPBO in compression-ignition ('diesel') engines is very challenging. FPBO is acidic, contains water, has a high viscosity (compared to diesel), is sensitive to polymerisation and difficult to ignite. Standard fuel injectors and fuel pumps will quickly corrode when used with FPBO.

Within SmartCHP a 1-cylinder test engine was modified to enable FPBO as fuel. Modifications include: a corrosion resistant fuel supply, a redesigned fuel injector & pump, increased compression ratio and dedicated engine control software. The dedicated fuel injector was constructed in-house. Eventually also a 4-cylinder, 48 kWe prototype was developed and tested.

The test engine was succesfully operated on FPBO's produced from different biomass. Typically 20 wt% ethanol was added to simplify the operation, but successful runs were also performed with just 10wt% EtOH or even without any EtOH. Hardly any difference in electrical efficiency was observed when fuelling FPBO or diesel. Typically, CO emissions are higher with FPBO and NOx lower compared to diesel, but in all cases flue gas treatment is required. **An important milestone in the project was achieved by running the engine for 500 hours on FPBO without changing fuel injection system.** Visual inspection of the injector showed only minor signs of wear.

Discover the results

Smart and flexible heat & power from fast pyrolysis oil (conference paper)

The use of untreated FPBO in compression-ignition engines is very challenging and we have been working on the topic for many years. In this project we were able to achieve stable operation for over 1,000 hours with minor impact on fuel injector and fuel pump. As far as I know, this is really unique in the world.

Bert van de Beld, BTG Biomass Technology Group

Sustainability of the system

The sustainability of the five SmartCHP value chains was assessed by BTG Biomass Technology Group, who conducted an **analysis of their potential GHG reduction and sustainability risks, from feedstock to end user.**

The sustainability assessment was based on three elements: the calculation of the carbon emission reduction of the value chains following the Renewable Energy Directive (RED II) methodology; the examination of value chains, according to sustainability topics covered in biomass sustainability schemes, such as biodiversity, impact on soil, water, and air; and the evaluation of other aspects, such as carbon debt, indirect land use change, and cascading use/circular economy.

89% **emission reduction**
COMPARED TO THE FOSSIL ALTERNATIVE

This analysis concluded that the five SmartCHP value chains present emission reduction values in the order of 89% to 97% compared to the fossil alternative. These values exceed the 70% minimum emission reduction established by RED II in case of electricity heating and cooling production from biomass fuels. **All SmartCHP value chains can therefore be accounted for national renewable energy targets and are eligible for financial support.**

Discover the results

Sustainability assessment
(report)

Life Cycle Assessment
(report)

Can new solutions win over bioenergy sceptics?
(interview)

The choice of feedstock is very important. Biomass is a very broad spectrum of different feedstocks, and each feedstock has its own merits – some can be very sustainable; and other can be not so sustainable.

Martijn Vis, BTG Biomass Technology Group

Consumer & public acceptance

The public acceptance of bioenergy production systems is critical to fully realise the transition towards renewable energy. Few studies have investigated the public backing of bioenergy and its related technologies, such as SmartCHP systems.

Within the project BTG and Exergia Climate Change Consultants conducted an analysis of the social acceptance of bioenergy systems in five EU countries: Sweden, Netherlands, Romania, Croatia and Greece. **Three dimensions of social acceptance were assessed: socio-political**, namely how policies and technologies are perceived by political stakeholders and the broader public; **community-level**, particularly relevant where local stakeholders and residents have the rights to oppose to bioenergy projects; and **market-level**, related to the adoption of these technologies by consumers.

It is expected to be possible to introduce SmartCHP systems without major social acceptance issues in Sweden, Croatia, Greece, and Romania. However, the socio-political acceptance of bioenergy is very low in the Netherlands. With respect to community acceptance, the SmartCHP systems should be designed in such a way that they generate low noise, low odour, low emissions, and low visibility; transparent communication with neighbouring communities about plans of installing SmartCHP units is also crucial. These two dimensions affect a widespread market acceptance, in terms of expectations of buyers and users of SmartCHP systems and of smooth permit procedures. Market acceptance is also influenced by promotional aspects, which can form important motivations to use SmartCHP technologies.

The analysis of these three dimensions contributes to the **elaboration of an appropriate market introduction strategy, which must be based not only on hedonic and normative reasons, but also on facts enabling rational decision-making for customers.** The involvement of policy makers is also important to ensure that SmartCHP technology becomes a common element in renewable energy plans of national and regional authorities.

Discover the results

Consumer and public acceptance assessment (report)

Financial and market analysis

Dowel Innovation and Exergia conducted a market assessment and profitability analysis related to the use of SmartCHP systems. This analysis identified the parameters affecting the financial sustainability of small-scale cogeneration units, considering different engine sizes as well as different sectors and countries of application.

Results showed there to be a high potential for application in commercial and tertiary sectors, and more specifically in six segments: hotels, office buildings, retail, hospitals, educational buildings, and greenhouses.

commercial and tertiary sectors

HIGH POTENTIAL FOR APPLICATION

From these promising market segments, seven use cases of different buildings with FPBO obtained by four types of biomass were analysed. The most significant factors effecting profitability were identified as being: Feed-in Tariff, Energy price, Operation expenditure, and Capital expenditure.

The use case analysis also demonstrated that **SmartCHP units can be combined with other means of renewable energy production, such as PV panels and wind turbines**. A hybrid configuration would be particularly suitable in cases where electricity needs are higher than heat needs, and where electricity prices are high.

One key benefit showcased by SmartCHP units is their flexibility, provided by the smart control, allowing the end user to select its favourite operation mode among heat-base, electricity-based, and economy-based options. This flexibility helps to maximise efficiency, profitability, and minimise emissions.

Discover the results

Market assessment
(report)

Financial and economic analyses for different use cases
(report)

Such a novel bioenergy solution based on fast pyrolysis of locally available biomass is designed to remain financially affordable for a large number of non-professional customers. The solution runs based on different types of biomass, which enables an easy-replicability in very different ecosystems, each with its own biomass availability.

Athanase Vafeas, Dowel Innovation

Policy recommendations

The European Parliament adopted the EU Climate Law in June 2021, which makes legally binding a target of reducing emissions by 55% by 2030 and achieving climate neutrality by 2050. The **SmartCHP system** can contribute to this transition by providing **renewable electricity and heat** to industries, district heating and large buildings. It is a **high-efficiency small-scale cogeneration unit** as defined in the 2023 recast of the Energy Efficiency Directive (EED), that contributes to increased use of renewable energy in heating and cooling as envisaged in the Renewable Energy Directive (RED III).

Compared to the rapid development of renewable electricity production, the uptake of renewable energy in the heating and cooling sector has been relatively slow. The JRC considers highly-efficient CHP and efficient district heating to be **key technologies in the future energy system** and recommends that they should be discussed as an option in the National Climate and Energy Plans by all Member States. The SmartCHP technology should become more known, and efforts should be made to include small-scale renewable CHP in national and regional level plans.

For the large-scale deployment of SmartCHP systems, **policy measures** are required to provide financial support, clear emission limits, and simplify permitting procedures, which will help **to reduce the transaction costs for final consumers and increase the market acceptance**.

Discover the results

Final recommendations
for policy makers
(report)

Assessment
of legal and regulatory issues
(report)

SmartCHP partners advocate the following:

1. **Develop EU wide emission limits for bioenergy** (CHP) installations with a capacity between 250 kW and 1 MW input.

2. **Change permitting rules** so that Member States require a notification, rather than a full environmental permit application, for SmartCHP systems.

3. **Continue the efforts to upgrade the Technical Report** (CEN/TR 17103:2017) “Fast pyrolysis bio-oil for stationary internal combustion engines - Quality determination” to a full standard.

4. **Develop a market introduction programme** in collaboration with national authorities, which includes the installation and monitoring of a number of SmartCHP installations. This will provide important emission data and other environmental and safety data for legislative authorities, which is needed for them to evaluate the possible simplification of the permit requirements.

5. **Change the Waste Framework Directive** in such a way that no end-of-waste statement is needed for using clean biomass that has been exempted from the waste regime of waste incineration plants for the production of energy, fuels or products.

Partners

- ABATO Motoren – Innovation in Power Generation
- btg – biomass technology group
- capax – Biobased development
- Dowel innovation
- DTU
- eXergia – Climate Change Consultants
- Greenovate! Europe
- OWI Science4Fuels an der RWTH Aachen
- TEHAG – Diesel Emission Management
- TU/e – Eindhoven University of Technology

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