Bio-FlexGen

BIOENERGY FOR A FLEXIBLE FUTURE

Popular scientific report

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The Bio-FlexGen project

Europe is moving rapidly towards a cleaner and more resilient energy system. Solar and wind power are growing fast, but their output changes with the weather and the time of day. To maintain a stable supply of heat and electricity, we need renewable technologies that can step in when the sun is not shining or when the wind is calm. Bioenergy is one of these options. It uses plant material and organic residues as fuel, and it can replace fossil fuels directly in many sectors.

The Bio-FlexGen project explores a new way to use bioenergy more efficiently. Its focus is the development of the Biomass Top Cycle, known as BTC. This is an advanced type of combined heat and power plant. A combined heat and power plant produces electricity and useful heat at the same time and is often placed close to communities or industries that need both. The BTC concept aims to raise the efficiency of these plants and give them the ability to operate flexibly throughout the year.

A key feature of the BTC idea is its use of gasification. Gasification is a process in which solid biomass, such as forestry residues, is heated with a controlled amount of air or oxygen. Instead of burning the material directly, the process releases a gas called syngas. Syngas can be burned in a gas turbine to generate electricity and heat. In the BTC concept, the gasifier can switch between two modes. One uses air and is suited for heat and power production. The other uses oxygen and makes it possible to produce hydrogen and a pure stream of biogenic carbon dioxide, which can be used in industry.

The BTC plant is designed to adapt to changing needs in the wider energy system. During cold months, when the demand for heat and electricity is high, the plant can operate in its most efficient heat and power mode. At other times, for example when electricity prices are low or when there is abundant wind and solar power, the plant can shift to the production of hydrogen. Hydrogen is a clean energy

carrier that can be stored, transported, or used directly by industries. The option to switch between modes provides a valuable level of flexibility that is important in future renewable energy systems.

Since the project started in 2021, fourteen partners from five European countries have taken part in developing and evaluating the BTC technology. Their work has included laboratory tests, computer simulations, economic assessments, and studies on environmental and social impacts. The project aims to understand how the key parts of the BTC system can work together. The main technical focus has been on creating a flexible gasifier and a gas turbine combustor that can operate with different fuels, including hydrogen.

Bio-FlexGen has now produced new knowledge that can guide the next stages of research and development. The project has provided insight into how the BTC plant behaves in different operating modes and how it might fit into national energy systems. It has also explored whether the technology is economically attractive for district heating networks and industrial sites. In addition, the project has examined how the technology affects society, from job creation to environmental performance.

This report presents the main findings of the Bio-FlexGen project. The following chapters describe the BTC plant, the development of the new gasification and combustion technologies, the performance of the plant in various energy contexts, and the wider environmental, social, and economic effects of the technology.

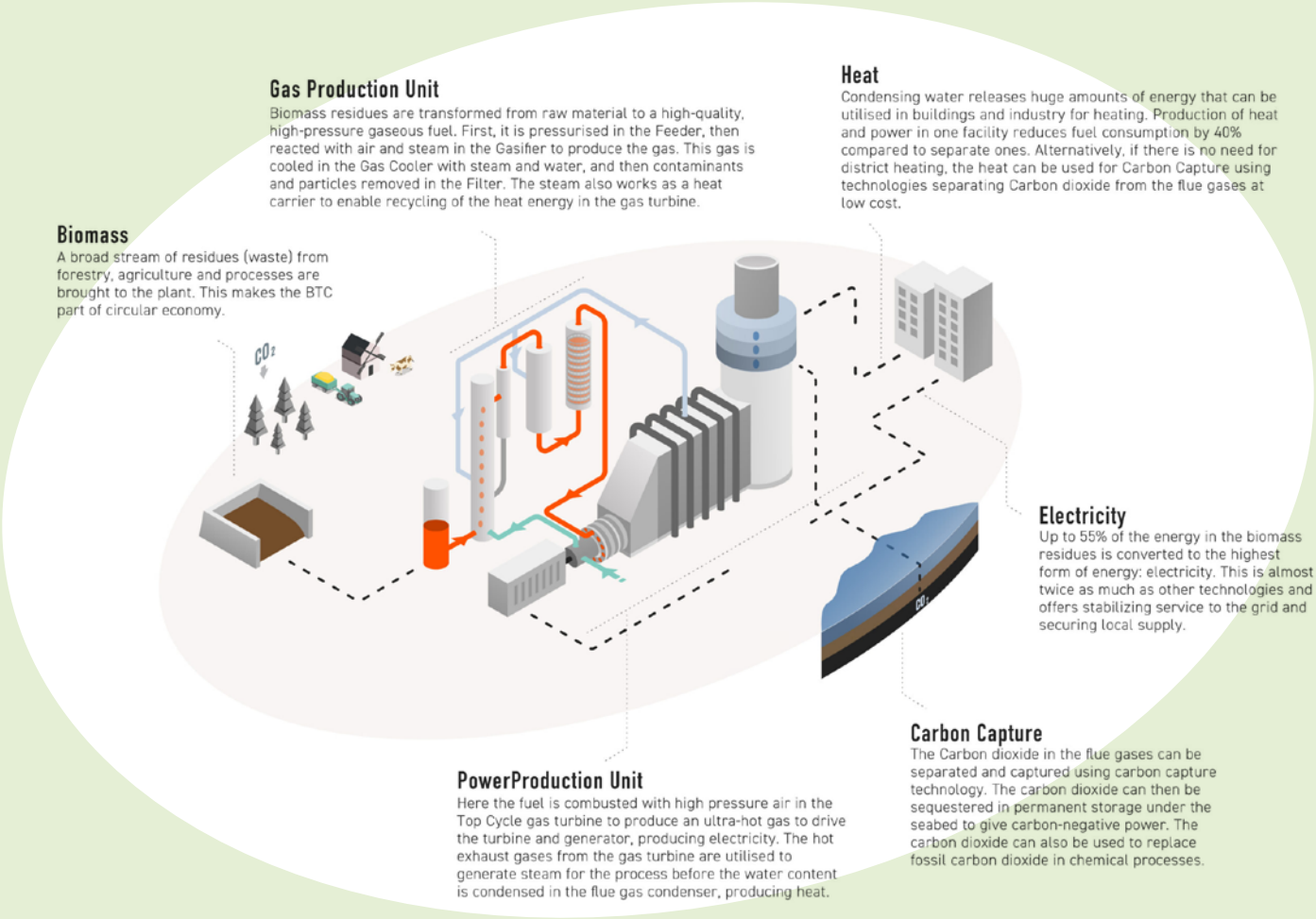
The Biomass Top Cycle Plant

The Biomass Top Cycle (BTC) plant is a new type of combined heat and power system that uses renewable biomass more efficiently and flexibly than conventional designs. Its central feature is a gasifier that converts solid biomass into a fuel gas called syngas. This gas can be burned in a gas turbine to produce electricity and useful heat.

A key innovation of the BTC concept is its ability to switch between two operating modes. With air in the gasifier, the plant works as a high efficiency heat and power unit. With oxygen, the same equipment can produce hydrogen and a pure stream of biogenic carbon dioxide for industrial use. This allows the plant to respond to seasonal changes in heat demand and to shifts in electricity prices.

The BTC plant also includes a specially designed gas turbine combustor that can burn both syngas and hydrogen cleanly and safely. This makes it possible for the plant to provide steady heat and power when needed, or to shift to hydrogen production when renewable electricity from wind and solar power is plentiful.

In this way, the BTC plant acts as a flexible energy facility that supports the wider energy system. It combines renewable biomass, efficient heat and power production, and the emerging hydrogen economy in one integrated concept.



Biomass Gasification Technology

Biomass plays an important role in helping industries reduce their carbon emissions. One promising way to use biomass efficiently is through gasification. Gasification converts solid biomass into a fuel gas that can be used in different energy systems, including modern gas turbines. Among the available technologies, fluidised bed gasifiers are especially attractive because they can handle many types of biomass and can be built in a wide range of sizes.

What are the limitations of today's gasification systems?

Most existing biomass gasifiers operate at atmospheric pressure. Their product gas needs to be cooled, cleaned, and then compressed before it can be used in a turbine. This results in significant energy losses, since heat is wasted during cleaning and some useful components are removed. To avoid these losses, new gasification technologies need to operate under pressure and work smoothly with high-performance gas turbines.

Conventional pressurised fluidised beds face several challenges. Bubbling beds, which operate at low gas speeds, struggle under pressure because they lose too much char and have difficulty moving the solid particles needed for steady operation. Circulating beds can run at higher speeds, but they can be complex to build and maintain, especially for the small and medium-sized plants used in district heating systems.

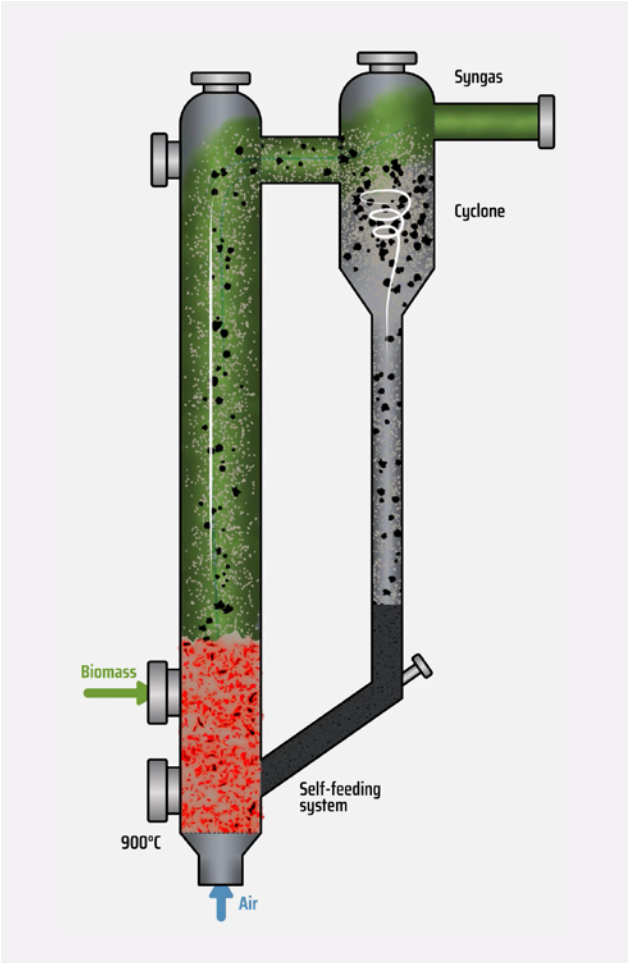
How does the Hybrid Fluidised Bed technology address these challenges?

The Bio-FlexGen project developed a new type of pressurised gasifier called the Hybrid Fluidised Bed (HFB). This system uses two types of bed materials at the same time. Larger particles create a turbu-

lent zone at the bottom of the reactor, which helps convert even big biomass pieces efficiently. Smaller particles move in a circulating loop together with the char, forming a stable upper region. This combined behaviour creates a robust and efficient gasification environment that works well at high pressure and is suited for integration with gas turbines.

How was the new technology tested?
To test the concept, the team built a pilot-scale pressurised cold flow unit and studied how the gas and solids move inside the system. The tests confirmed that the hybrid bed behaves as intended and that key components such as the gas distributor, riser, cyclone, and return pipe perform reliably under pressure.

The team also carried out oxygen-blown gasification tests for hydrogen production. These tests showed that the system can operate stably under a wide range of conditions. Several bed materials were evaluated, including iron-based particles that can act both as oxygen carriers and as catalysts for breaking down hydrocarbons. The gasifier can switch between air-blown and oxygen-blown operation, giving it flexibility for different energy applications.



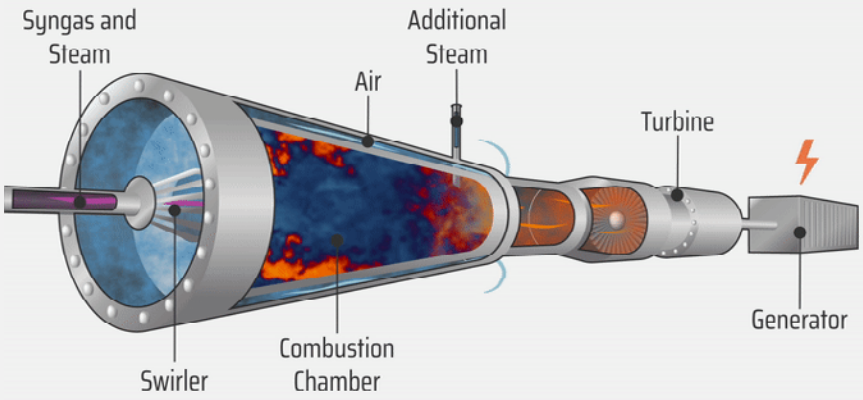
Flexible Gas Turbine Combustion Technology

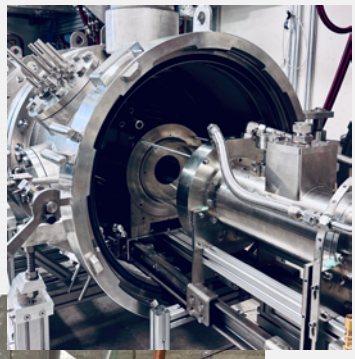
Gas turbines play an important role in providing reliable electricity and heat. As Europe moves towards cleaner energy sources, these turbines must adapt to new fuels such as renewable gases and hydrogen. Hydrogen behaves very differently from natural gas. It burns much faster and can cause the flame to move back towards the burner, while some renewable gases burn more slowly and risk the flame going out. Developing a burner that can handle both extremes safely is therefore a major challenge.

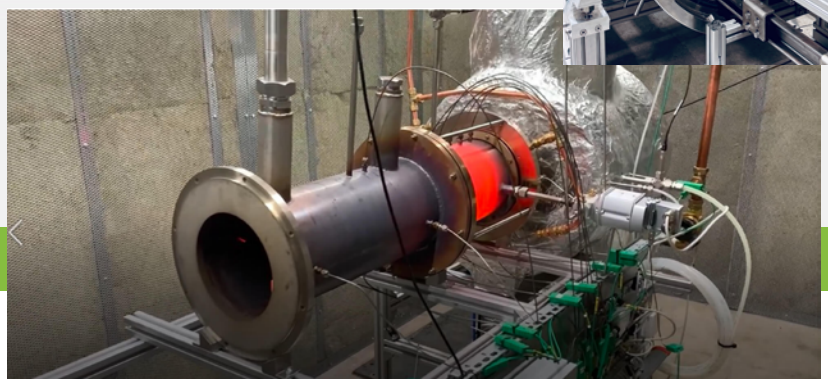
The Bio-FlexGen project has designed and tested a new burner that meets these demands. The research team first studied the internal air flow of the burner in a water tunnel to understand how the movement of air and steam helps to stabilise the flame. They then carried out combustion tests in the laboratory using natural gas, hydrogen, and mixtures of the two. These tests also included switching the fuel during operation, which reflects real situations in future energy systems.

The burner showed stable operation across the full range of fuels, from one hundred per cent natural gas to one hundred per cent hydrogen. It produced very low nitrogen oxide emissions, even under humid conditions. The team was also able to demonstrate smooth fuel switching, which is important for future power plants that must react quickly when the supply of wind or solar electricity changes.

How does this research connect to the wider scientific field?
The findings from this work support a broad international effort to make gas turbines compatible with hydrogen and other renewable gases. Many







research groups and companies are trying to create burners that remain stable under changing fuel conditions while keeping emissions at very low levels. A common difficulty in the field is achieving clean combustion without compromising safety or flexibility.

The Bio-FlexGen burner adds new experimental evidence that this balance is possible. Its ability to stabilise flames across a wide range of fuels confirms that carefully shaped internal air flows can prevent problems such as flashback and blowoff. The results also reinforce the view that humid hydrogen combustion can be operated cleanly with very low nitrogen oxide formation. This supports global research trends towards using water or steam dilution to reduce emissions.

What do these results mean for the future?

As Europe increases the share of renewable electricity, power plants will need to operate more flexibly. They may run only at certain times of the day or year, depending on market conditions and weather patterns. They will also need to accept fuels that vary in composition. The new burner design developed in Bio-FlexGen helps to meet these requirements.

In the future, this type of combustor could allow gas turbines to run safely on hydrogen when it is available, and on mixtures of hydrogen and renewable gases at other times. It could also support combined heat and power plants that shift between electricity generation and hydrogen production. By enabling flexible and low emission operation, the technology helps to reduce reliance on fossil fuels while keeping energy systems stable.

Overall, the work carried out in Bio-FlexGen provides a solid scientific foundation for the development of hydrogen-ready gas turbines. It shows that clean and reliable combustion is achievable and that new designs can meet the needs of a future low carbon energy system.

Performance and Integration of the BTC Technology

The Bio-FlexGen project examined how the Biomass Top Cycle (BTC) plant performs in different operating modes and how it fits into real energy systems. The aim was to understand whether the technology can provide reliable heat, electricity, and hydrogen while remaining flexible and economically attractive.

How does the BTC plant perform in practice?
Computer simulations showed that the BTC plant can operate in several ways: as a high efficiency heat and power unit, as a fast responding hydrogen-fired turbine, or as a producer of hydrogen and biogenic carbon dioxide. The plant can shift between these modes based on energy demand and market conditions. In winter it can supply heat and power, while in periods of low electricity prices it can switch to hydrogen production.

How does the technology work in real energy systems?
The project applied the BTC concept to two types of cases:

- A Swedish district heating system
- Industrial sites in Spain, including chemical and cement plants

In Sweden, BTC integration increased renewable electricity production and improved system flexibility. However, investment costs remain a barrier under current market conditions.

In Spain, BTC plants improved profitability and reduced carbon dioxide emissions in every scenario studied. Industrial users with steady heat demand appear especially well suited to the technology.

How does BTC fit into national energy systems?
National simulations for Sweden and Spain showed that BTC technology can support renewable expansion by providing flexible heat and electricity. In Sweden it becomes more attractive when the system needs additional electricity generation, especially in later years. In Spain it helps meet renewable targets and reduces electricity costs, particularly in the 2030 scenario.

Where can the technology be replicated?
Geographic studies identified promising regions in Spain, Germany, and Sweden based on biomass availability and industrial demand. Stakeholder analysis also indicated general support for technologies that reduce emissions and use local resources.

What does this mean for the future?
BTC technology can contribute to clean, flexible, and reliable energy systems. It supports the shift away from fossil fuels by offering renewable heat, electricity, and hydrogen. Although investment costs are still high, the long term potential is strong, especially in industrial settings and district heating networks.

Environmental, Social and Economic Impact

The Bio-FlexGen project assessed how the Biomass Top Cycle (BTC) technology affects people, the environment, and the wider economy. The results show that the technology can support a fair and sustainable energy transition when it is designed and operated responsibly.

How does the technology influence employment and skills?
BTC technology creates new jobs in plant operation, maintenance, construction, and the biomass supply chain. Most of these positions are medium to high skilled and offer long term employment. Workers also gain new technical skills that support Europe's shift towards low carbon technologies. Additional jobs appear in related sectors such as manufacturing and logistics, benefiting regional labour markets.

How does it support local development?
BTC plants use local biomass, often collected from forestry and agricultural residues. This brings economic activity to rural areas and creates opportunities for local suppliers. Because the technology reduces reliance on imported fossil fuels, more of the value of energy remains within the region. This strengthens economic resilience and supports a circular bioeconomy.

What are the effects on community well-being?
The technology is designed to use only residues and by-products. This avoids competition with food production and reduces the risk of environmental pressure on land. Using locally available resources also supports traditional rural livelihoods and helps maintain healthy forest and agricultural systems.

How is the technology viewed by the public?
Communities generally view BTC technology positively. People appreciate the link between renewable energy, lower emissions, and local economic benefits. Trust increases when operators and authorities communicate clearly and involve local residents early in planning. Service quality and stable pricing remain important in district heating applications.

What did the life cycle assessment show?
The Bio-FlexGen project carried out a life cycle assessment (LCA) to understand the environmental impacts of two combined heat and power (CHP) plants. The first was an existing biomass CHP plant in Linköping, Sweden. The second was the new Biomass Top Cycle (BTC) process developed within the project. The aim was to compare their performance during operation and to assess the environmental potential of the BTC technology. The study focused only on the operational stage of each plant and compared the impacts for producing the same amount of heat.

The assessment showed a clear result: the BTC technology causes much lower environmental impacts than the existing plant.

Compared with today's system, the BTC process reduces:

- **Climate impact** by almost 80 per cent
- **Air pollution that leads to acidification** by about 90 per cent
- **Freshwater pollution** by more than 90 per cent
- **Land use** by about 30 per cent
- **Dependence on fossil resources** by about 90 per cent

In some categories, such as human toxicity and water use, the extra electricity produced by the BTC plant actually creates a net environmental benefit. These improvements come mainly from the higher efficiency of the BTC process, which makes better use of biomass and produces more electricity per unit of heat.

The study also showed that transporting biomass can influence several impact categories. In future work, it will be useful to examine transport distances and fuel sourcing more closely. Overall, the assessment suggests that BTC technology can significantly reduce environmental impacts when used in district heating or industrial energy systems.