11th IGTC
Dispatchable technology & innovations for a carbon-neutral society
10-11 October 2023, Brussels, Belgium
Paper ID Number: 11-IGTC23

BTC – A NEW TECHNOLOGY FOR HIGH EFFICIENCY BIOPOWER IN A DECARBONISED SOCIETY

Michael Bartlett, Felix Guethe, Jens Pålsson, Chunguang Zhou, Christian Oliver Paschereit, Henrik Båge

Phoenix Biopower AB, Drottning Kristinas väg 18, 114 24 Stockholm, Sweden
Email: michael.bartlett@phoenixbiopower.com

ABSTRACT

To limit global warming, meet growing global energy demand and to increase security of supply, enormous investments are now being made in renewable electricity generation. A high-efficiency process, called the Biomass-fired TopCycle (BTC), is being developed by Phoenix BioPower to address this market. By increasing the electrical efficiency, a cost-efficient and scalable solution is provided. As the primary fuel is biomass, carbon dioxide removals (negative emissions) can be achieved when combined with CO_2 capture and sequestration. Further attributes are a high fuel flexibility including 100 % hydrogen utilization and good off-design performance, therefore allowing a dispatchable and flexible solution for renewable energy.

This paper presents the BTC process, and associated components, and evaluates among others a new patented gasifier design for efficient and cost-effective operations at pressure. The BTC cycle is compared to conventional cycles and the improved performance of BTC is explained. Further, the BTC development program is described including the commissioning of a so-called fuel-to-flame test rig. From a commercial outlook the potential for the BTC concept to decarbonize our energy systems in different applications is promising, including cost-effective negative emissions in BECCS applications. The product range is presented, from 10 to 100 MWe to address the market for renewable power, heat, and negative CO_2 emission.

INTRODUCTION

To restrict global warming to 1,5° C, or even 2°C, while meeting growing global energy needs will require an enormous growth in renewable electricity generation, as much as 1000 TWh/a (IRENA 2020) Further, Negative Emissions Technologies (NETs), e.g. bioenergy carbon capture and storage (BECCS), are highlighted as a central measure to decrease atmospheric CO_2 levels, and most scenarios that meet the Paris Agreement targets now include extensive deployment of NETs (IPCC 2018). Lastly, hydrogen and hydrogen vectors such as ammonia and methanol, are seen by many as a key pathway to both decarbonize industry and provide peak power.

Biopower, or the production of electricity from biomass fuels, has the potential to provide a crucial, renewable complement to intermittent wind and solar power (IEA 2017). Modern, sustainable processes allow biomass utilization to be near climate neutral as the CO_2 released during combustion is absorbed by new biomass growth. In addition, biopower can also provide negative emissions, if implemented with carbon capture and storage, giving the twin benefits of decreasing present emissions from power and heat generation, and offsetting hard-to-abate or past CO_2 emissions (Lehvin 2019).

Currently, biomass and waste are the largest renewable energy source globally, providing 9.4% of total primary energy (IEA, 2019). The role of bioenergy is expected to grow, with IPCC, IEA and IRENA net zero scenarios showing 100-160 EJ/a bioenergy by 2050, or 18-28% of primary energy. These scenarios consider technical and sustainability limits, but not political ones.

However, due to the poor economics of conventional boiler plants, the market penetration of biopower has been limited. In addition, supply chains are still not well developed. While boiler plants are a mature technology, corrosion issues in the superheater and economics usually limit electrical efficiency to 20-33% at 10 – 100 MW_{fuel} scale (Beiron 2022) at 10-30 €/MWh fuel cost. Consequently, biopower is mostly found in combined heat and power applications, where heat is the primary product, e.g. district heating, or where high subsidies are provided.

Phoenix BioPower is developing a new solution, called the Biomass-fired Top Cycle (BTC), to radically increase plant efficiency, decrease fuel costs and thus enable the broad application of biopower to generate renewable power on demand. Thanks to relatively high temperature waste heat, BTC can reduce costs for CO_2 capture and negative emissions. Further, the gas turbine is naturally suited to utilize hydrogen as either a primary or secondary fuel.

The purpose of this paper is to introduce the BTC cycle and performance, the main equipment required, the development pathway and to outline its potential in the decarbonized energy system.

NOMENCLATURE

BECCS – Bioenergy and CCS
BECCU – Bioenergy and carbon capture and utilisation
BIGCC – Biomass Integrated Gasification Combined Cycle
BTC – Biomass-fired TopCycle
CAPEX – Capital Expenditure
CCGT – Combined Cycle Gas Turbine (power plant)
CCS – Carbon Capture and Sequestration (or storage)
CFD – Computational Fluid Dynamics
CHP – Combined Heat and Power plant
DP – Pressure drop
ECO - Economizer
FBN – Fuel Bound Nitrogen
FGC – Flue Gas Condenser
GPU – Gas Production Unit
HHV – Higher Heating Value
HRSG – Heat recovery steam generator
IEA – International Energy Agency
LBO – Lean Blow Out
LCOE – Levelized cost of electricity
LHV- Lower Heating Value
LP – Low Pressure
LPG – Liquefied Petroleum Gas
MILD – Moderate or Intense Low oxygen Dilution
NET – Negative Emissions Technology
OPEX – Operational Expenditure
PACS – Phoenix Advanced Combustion System
PM – Particulate Matter
PPU – Power Production Unit
PSR – Perfectly Stirred Reactor
SCR – Selective Catalytic Reduction
STIG – Steam Injected Gas Turbine
Tinlet – Inlet temperature
TGA – ThermoGravimetric Analysis
TRL – Technology Readiness Level
t_{ext} – Extinction time (for PSR)
ϕ – Equivalence ratio combustion
Ω – Steam to air ratio combustion

BTC – THE EFFICIENT BIOPOWER PLANT

The Biomass-fired Top Cycle (BTC) is a high-efficiency humid gas turbine cycle that utilizes low-cost biomass streams as primary fuel and gaseous fuels as secondary fuel, e.g. hydrogen, for fast response. The inherent features that contribute to high performance are:

- Massive steam injection in the gas turbine and therefore less air compression
- Near-stoichiometric combustion in so-called MILD conditions for low emissions and high fuel flexibility
- High pressure gasification of biomass in a new, compact and efficient gasifier concept.
- Integration of syngas clean-up system and steam injection for optimal heat recovery
- Waste heat available at high temperature (thanks to high steam contents of flue gases)

The concept of the BTC plant is illustrated in Figure 1, along with an outline of the main process steps. The BTC plant consists of two main sections: a gas production unit (GPU) and power production unit (PPU), whereby:

- The GPU consists of a low temperature biomass dryer, biomass pressurization and feed system (pre-treatment), gasifier, direct gas cooler and hot gas filter

- The PPU consists of a high-pressure gas turbine with steam-injection, called the TopCycle. This includes a gas turbine, heat recovery steam generator, flue gas condenser, and water treatment.

In the Gas Production Unit biomass is first dried utilizing a belt-dryer driven by 80°C hot water from the flue gas condenser. It is then pressurized in a lock-hopper with inert gas such as nitrogen and prepared for screw feeding to the gasification unit. The gasifier then utilizes steam and compressed air as gasifying agents and raises the temperature, up to around 900°C, converting the biomass to a gaseous fuel for use in the TopCycle. The hot gases are directly cooled with water and steam to 400-500°C and led to a hot gas filter to remove particles and alkali contaminants, before entering the combustor of the TopCycle gas turbine.

The power island is built around a TopCycle gas turbine that uniquely operates with over 50% steam in the turbine. Superheated steam is obtained in the BTC through utilizing cycle waste heat; first by raising steam in the heat recovery steam generator (HRSG) of the exhaust, and then by direct superheating through injecting it in the hot gas cooler.

After efficiently recovering this sensible energy in the exhaust, the latent heat is recovered by cooling the exhaust gases down to around 50°C in a flue gas condenser, thereby recovering water for the process. The resultant heat output is suitable for thermal processes such as fuel drying, district heating, district cooling, CCS or heat-to-power. Through this unique integration, waste heat is first recycled at high temperature to the gas turbine for the highest possible conversion to power and then utilized at low temperature for heat processes, allowing both high electrical efficiencies and high total efficiencies.

When compared to biomass gasification integrated with combined cycle (BIGCC), the efficiency potential of BTC is higher than combined cycles.

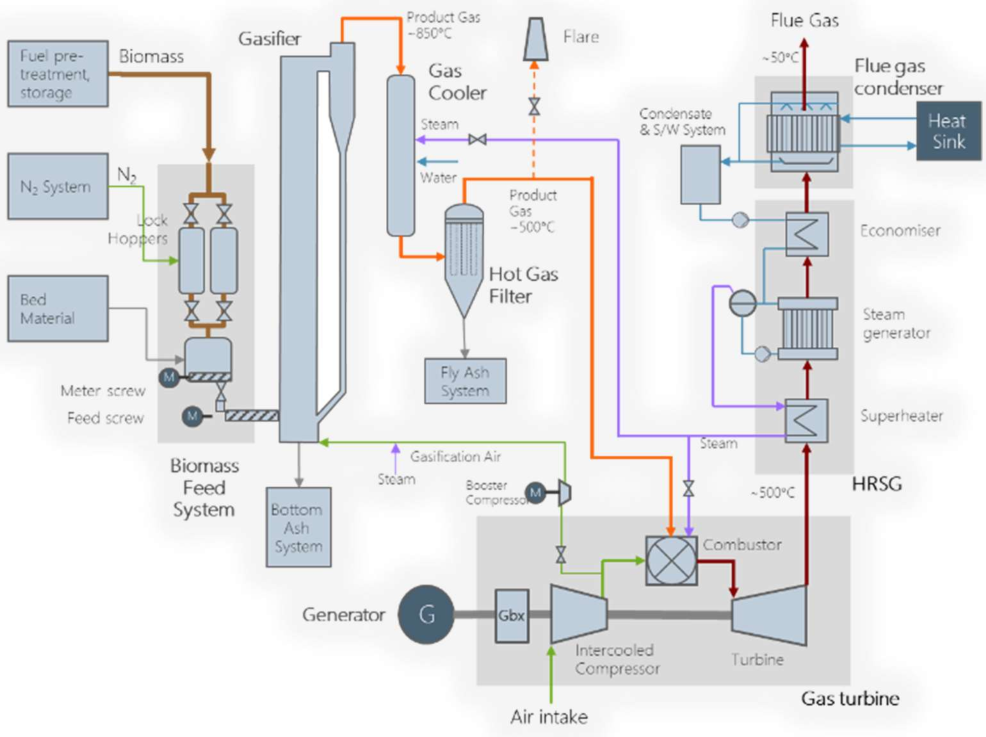

Figure 1: BTC simplified process schematic.

This is because the gasification waste heat is utilized in the gas turbine (topping) cycle, rather than the less efficient steam bottoming cycle. Further, waste heat from the flue gas condenser is used in BTC to dry the fuel, rather than extracting LP steam or using similar methods that penalize the combined cycle. Lastly, the BTC is designed to utilize the bio-syngas and high steam contents, so engine de-rating is not required.

THE GAS PRODUCTION UNIT

The gasification unit is used to produce clean product gas for use in the TopCycle combustion system. The combustible product gas is first produced via biomass thermal conversion in a proprietary pressurized fluidized bed gasifier, and then further cleaned to a desired level before entering the gas turbine combustor. A detailed description is given below.

Feedstocks

As biomass is a non-homogenous fuel that varies widely between markets, a key target of the BTC plant is to be fuel flexible. Further, as economies become circular, focus is on sustainable but usually low-quality sources of biomass, e.g. residues from forestry and agriculture. Forest residues are envisioned as the main feedstock of the first BTC plants, as this is widely used in biomass-fired CHP plants today. Plant economics, however, can be greatly improved when blending, or fully utilizing, low-grade fuel, e.g. straw and demolition waste.

Table 1: Typical properties of biomass feedstocks: a: (ERC, NL 2015; Hanula 2012); b: (ERC, NL 2015; Bhaird 2014); c:(Simeone 2013; Skoglund 2016; Krook 2004; Faaij 1997).

Feedstock	Forest residues (a)	Straw (b)	Demolition Waste (c)
Moisture, wt.%	4-50	4-50	19-50
Proximate analysis, wt.% dry basis			
Volatiles	74-85	71-81	(varies sign.)
Fixed carbon	16-23	20- 20	(varies sign.)
Ash	0.2-4.8	3.6-11	0.9 -24
Element analysis, wt.% dry basis			
C	43-54	40-52	44-52
H	5-6.5	5-6.2	5.5-6.6
O	38-50	40-54	33-44
N	0.4-2.4	0.6-1.44	0.1-1.3
S	<0.1	0.02-0.25	0.03-0.61
Cl		0.12-0.5	0.03-0.88
Major elements, g/kg (dry)			
Potassium (K)	1.1-3.6	10.0-17.0	1.2
Sodium (Na)	0.1-0.6	0.2-0.5	1.1
Silicon (Si)	1.8-3.9	8.0-33.0	9.9

Biomass characteristics include size, shape, bulk density, moisture content, ash content, alkali content. Typical properties and composition of target feedstock in the TopCycle plant are shown in Table 1. Straw contains a high level of alkali-rich ash and therefore is considered as a challenging fuel feedstock in fluidized bed gasifiers and boilers due to bed agglomeration issues. However, the bed agglomeration can be effectively mitigated, e.g. selecting proper bed materials and additives, lowering operating temperature, and controlling alkali levels in the bed. Moreover, demolition waste might contain high levels of trace elements, e.g. Zinc, which could cause corrosion issues in the gas turbine or HRSG, and thus needs to be addressed in the clean-up unit prior to the gas turbine (Jones F. 2013) and (Rocca E. 2008). The moisture content in feedstock could be up to 50%, and even higher for some extreme cases. Unique for gasification processes, the TopCycle system is designed to accept fuel feedstock with a relatively high moisture content, up to around 30%.

Feed System

Fuel Handling

Conventional fuel handling systems are used in the BTC plant. As the BTC utilizes a fluidized bed gasifier, feedstock particles up to 20-50 mm can be accepted, simplifying feedstock preparation to chipping or shredding. This contrasts with the very energy-intensive pulverizing equipment for an entrained-flow gasification system. To prevent issues in the fluidized bed gasifier, large inert and metal pieces in feedstock are separated using gravity or magnetic methods, especially for heterogenous demolition waste. Large pieces of combustible components could be screened out in a screening process and sent to a grinding unit to be shredded into small pieces.

Some low-density feedstocks, e.g. natural straw, could exhibit a bridging issue in the feeding hopper. Thus, actions to increase the bulk density, e.g. briquetting, are required to increase the flowability of the low-density feedstock in the feeder.

In addition to the gasifier product gas several gaseous or liquid fuels can be used for power generation as explained in the combustion section.

Dryer

High or uneven moisture content in the feedstock could reduce the operating temperature in the gasifier, resulting in a lower gasification rate and higher tar yield. It is also not optimal from a plant performance point of view to evaporate too much water contained in fuel. The selection of drying technology highly depends on local factors, e.g. power and heat demand, emission requirements and is driven by economics and plant type. In the BTC plant, biomass with moisture higher than 30% is typically sent to a belt dryer after grinding. The belt dryer, using air as drying media, is driven by 50-80°C hot water from the flue gas condenser. The drying process consumes energy at a low temperature and rejects heat at even lower temperatures, penalizing the total efficiency (heat + electricity). However, drying in general increases the biomass heating value, which increases the gasifier yield and electrical efficiency. Another commercial drying technology uses circulated steam as drying media in a closed-loop pressurized system, where steam from the cycle is needed but the dryer's waste heat can be utilised afterwards by external consumers. This high temperature drying process increases the total efficiency but penalizes the electrical efficiency compared to the low temperature dryer.

Gasifier feed system

The feedstock feeding system adopts a conventional N_2-driven lock hopper feeding system. This has been demonstrated at several plants for reliable pressurisation of biomass. A variable-speed metering screw at pressure sets the fuel flow, and therefore load of the BTC plant, while a fast-rotating feed screw transports the biomass into the gasification system.

Gasification and Hot Gas Clean-Up

Gasifier

Phoenix is developing a patented gasification technology especially suited to the requirements for BTC operation. This unit is based on the principles of air-blown fluidized bed gasifier; a technology that has been demonstrated at near-commercial scale with very high fuel flexibility and carbon conversion over 97% (K.Salo 1998) (Ståhl 2004).

The main features of the Phoenix pressurized fluidized bed gasifier include:

- High gasification rate under high pressure via good mixing of biomass feedstock, bed materials and gasification agents.
- Optimization of operating temperatures in both bed and freeboard zones by staged air injection, proper bed materials selection.
- High carbon conversion efficiency via minimizing carbon loss in bottom and fly ashes.
- Short start-up time (<2 h hot start) and fast response to the change of power (>3 %/min) output required for grid power peak shaving and valley filling. For gaseous fuels with no gasifier in operation, start-up time and ramp rates are quicker.
- Operate in a wide load range of 20%-100%, at pressures, up to 45 bar at very large scale.

Gasification air is extracted from the gas turbine compressor and mixed with a small amount of steam from HRSG prior to entering the gasifier. The hot mixture of steam and air enters the bottom of the gasifier via an air distributor, acting as fluidization gas and gasifying agents. Biomass feedstock, fed from the side of the gasifier, is well mixed with the gasifying agents and partially oxidized in the gasifier, producing combustible product gas containing carbon monoxide, hydrogen, methane, and inert gas components. Secondary air can be injected to increase the operating temperature in the freeboard section and enhance tar cracking.

Gas cooler

Phoenix is designing a unit for the partial quenching of syngas by injecting water and steam in the cooler. This maximizes the power output and efficiency of the gas turbine while avoiding troublesome convective heat transfer surfaces that easily foul in the ash "sticky" zone. The vapor-phase alkali metals, in the raw product gas from the gasifier, condense and deposit on the surface of solid particles in the cooler, which can be effectively removed using a particulate filter downstream.

Hot Gas Filter

To meet turbine requirements and protect gas turbine from corrosion caused by alkalis, high-temperature filtration by rigid ceramic/metal candles or tubes is adopted in Phoenix gasification system to remove both dust and the alkalis that have deposited on the surface of solid particles in the gas cooler. When cooling down the product gas to 500-600 °C before the filter, both Na and K can be effectively removed from the product gas to a level below 0.1 ppmw which is acceptable for the downstream gas turbine (Ståhl 2004) (P.Ståhlberg 1992). Other inorganics found in low quality fuels can similarly be removed with this method. The dust level after the high temperature filter could also be reduced to <5ppmw (K.Salo 1998).

Product Gas Characteristics

The heating value and composition of the product gas is critical to the TopCycle combustion process. The range of lower heating value and main gas compositions of the product gas prior to the combustor is given in Table 2.

Table 2: Target composition of product gas prior to gas turbine combustor in a BTC plant

	Range
H2, vol.%	4-7
CO, vol.%	5-9
CO2, vol.%	7-10
CH4, vol.%	3-5
N_2, vol.%	15-20
H_2O, vol.%	50-60
Particulate matter, ppmw	<5
Alkali, ppmw	<0.1
Benzene and tar, g/Nm^3 (dry basis)	<20
LHV, MJ/Nm^3 (wet basis)	3-4

THE POWER PRODUCTION UNIT

Phoenix Advanced Combustion System (PACS)

In the BTC concept, the combustor must operate near stoichiometric conditions with low-calorific gases diluted with steam. To meet this challenge, the Phoenix Advanced Combustion System (PACS) has been developed. This system is being designed to take advantage of the opportunities presented by highly diluted working fluid in the Top Cycle concept to ensure very high fuel flexibility, i.e. from bio-syngas to blends of methane and hydrogen (Dybe 21).

The fundamental concept of PACS is to stabilize combustion with a swirl burner utilizing induced vortex breakdown for flame stabilization as well as coupling to intense internal recirculation (Palulli, et al. 2023). In the BTC plant, the fuel is delivered already as a highly diluted mixture at high volume flow. For the flame this means that the constraint for homogeneity is at the combustor exit (complete oxidation), not at the burner (premixing). To operate with a wide range of fuels and loads, the steam content, combustion inlet temperature (T2) and equivalence ratio can be varied with limited impact on power and efficiency.

The operation, at ultra-wet conditions, has been demonstrated for various fuels at atmospheric as well as at elevated pressures (P. Kuhn, 2015) (P. Stathopoulos, 2016). Stable operation with low emissions has been demonstrated. Operating in oxygen depleted media is a way to greatly reduce reactivity (i.e. for H_2) and NO_x formation. Such conditions are often referred to as MILD (Moderate or Intense Low oxygen Dilution) or flameless conditions (De Joannon 2000). The low NO_x emissions for oxygen depleted conditions are well known and were described (Cavaliere, 2004), (Li 2011) (F. Guethe 2011) (F. Güthe 2009) (Elkady 2011). A key difference to conventional gas turbine combustion in air is that the high dilution reduces the maximum adiabatic flame temperature (and O_2 content) to values near the turbine inlet temperature and therefore also reduces the expected thermal NO_x emissions. In addition, this also acts as a safety measure to prevent flashback from stoichiometric or rich zones (in the oxidizer medium) with the ability to hold flames. This is shown in Figure 2 for pure H_2 fuel. The adiabatic temperature is determined by equivalence ratio ϕ (fuel flow) and steam ratio Ω. At high steam dilution as is common in the humid cycle the adiabatic temperature is at moderate levels even close to stoichiometric conditions (ETN 2022). At engine conditions the inlet temperature for gaseous fuels might be slightly lower depending on the steam addition, which can be used to further control the flame reactivity.

While the combustor has already shown promising results at TU Berlin (S. Göke 2014) with H_2 /CH_4 mixtures, the BTC syngas mixtures have been reported recently (K. Zhang 2020), (F. G. S. Dybe 2021) as well as 100% H_2 (Dybe 23). The current focus of development is on weak gases in terms of stability but also on impurities like tars formed in the gasifier and nitrogen containing species bound to the feedstock fuel. Keeping the steam temperature high has stabilizing effects. As high pressures are most expensive to test experimentally, focus is also on modelling including detailed kinetics and simulations using sophisticated CFD models (Palulli, et al. 2023). The design of the PACS is based on flow field modelling, atmospheric experimental data and uses chemical kinetics to assess operational envelopes and to transfer between operating conditions. A rough scaling from atmospheric testing to engine conditions for bio syngas can be done using Figure 3. A transfer of conditions along the horizontal arrow symbolizes atmospheric testing for high pressure conditions. Note the relatively small change in horizontal direction vs the steep change along the vertical line (ϕ).

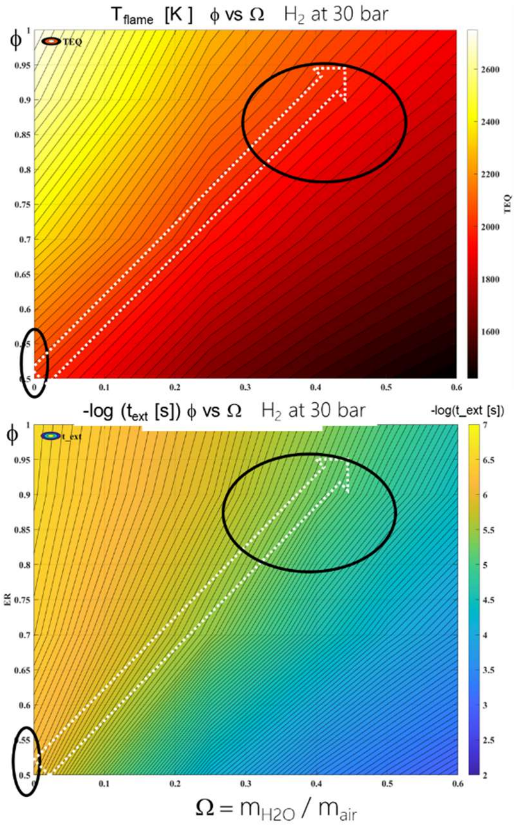

Figure 2: Contours of adiabatic temperature (above) and extinction time (below) of equivalence ratio ϕ and steam ratio (Ω) for hydrogen combustion and a wet cycle at 30bara and 500°C T_{inlet}. An operational regime for lean premixed condition shifting towards humid rich conditions is indicated.

A simple but well-proven concept to develop combustors for various fuel conditions utilizes detailed kinetics in perfectly stirred reactor (PSR) simulations to assess the flame stability, including the determination of the flame extinction time (t_{ext}) as a measure of reactivity. The t_{ext} refers to the minimum residence time of a PSR at given inlet condition before blowing out. It can be determined in an iterative procedure by changing the residence time. The extinction time t_{ext} is a measure of the chemical time scale and usually << 1ms (shown as -log (t_{ext} >3 in Figure 2 and Figure 3). The kinetic mechanism is a version of the AramcoMech 3.0 from the Combustion Chemistry Centre in Galway (C-W. Zhou 2018).

To study the operational envelope, the combustor is operated within the stability limits between lean blow out (LBO) and flash back. The LBO is a considerable risk for weak gases of low reactivity, which rely on high inlet temperature and proper flame stabilization by the swirler.

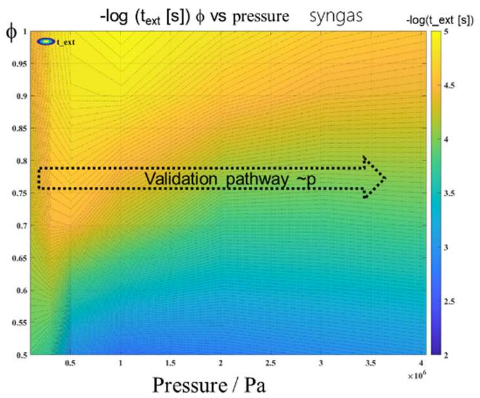

Figure 3: Dependence of key reactivity parameter extinction time on pressure for bio-syngas.

To achieve fuel flexibility, bio-syngas fuel must be substituted with other gases. This is a challenge for common premix combustion systems, since different heating values and densities result in variation in Wobbe index, which then complicates the design for a good combustor performance, i.e. allowing moderate pressure drop for all conditions and safe operation. A second difficulty is the chemical reactivity, i.e., keeping the flame from LBO on the low reactivity spectrum of fuels, and from flash back at high reactivity.

Flash back safety is determined by extinction time at stoichiometric conditions (Blouch 2011) (Lieuwen 2008) (M. Zajadatz 2018) and includes the flame holding ability. This risk is largely reduced in PACS by operating highly diluted at near stoichiometric conditions, i.e., due to the lower overall temperature and reactivity. The stoichiometric flame in PACS then actually represents the highest risk situation. This contrasts with conventional systems relying on fuel injection into the air stream, where the flashback risk is near the fuel injector. The range of total reactivity has been demonstrated by the TU Berlin combustion system (M. Y. S. Dybe 2023) and can be further extended. Operation can be switched at the operating rig for blends from 100% CH_4 to 100% H_2 at single NO_x emissions at atmospheric conditions.

A further design feature is the introduction of the "Double Swirler" burner, which has been experimentally described by (M. Y. S. Dybe 2023) and simulations by (Palulli, et al. 2023). In that concept the air and the weak fuel at high volume flow are introduced into the combustor by two swirlers integrated into the burner body. The separate inflow into the mixing region results in very late contact of fuel and oxidizer in the flow. This leads to relatively poor mixing, which is less important within highly diluted flames. Crucially, however, it leads to increased flashback safety since even a reaction early in the mixing region is relatively safe (at low pressure and startup conditions) because the flame is not close to the metal parts of the mixer. A high strong swirl of fuel and air creates a highly turbulent flow and a vortex breakdown zone in the heat release zone. This leads to a strong inner and outer recirculation in the combustor, creating a long reaction zone where low reactive fresh gas can react with hot exhaust gas. The high dilution and low oxygen content in the reactor is typical for MILD conditions, which are insensitive to mixing quality with respect to NO_x. In this PACS combustor the NO_x is not determined by the thermal pathway as in conventional GTs. For the bio syngas the highest contribution to NO_x emissions comes from the fuel bound nitrogen (FBN), which depends on the feedstock and gasifier operation. FBN-NO_x can be minimized by designing a large combustor with rich zones in the heat release zone (Yang, et al. 2023) (Raslan A. 2023).

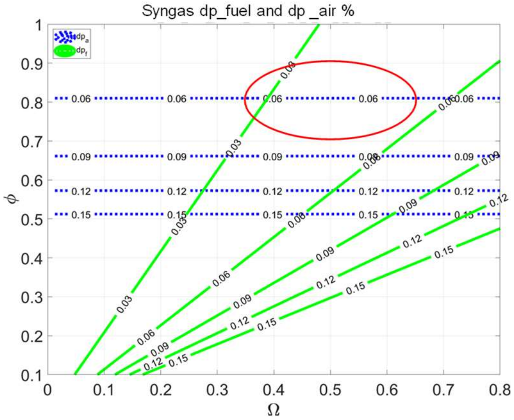

Figure 4: Relative pressure drop for air (blue - dotted) and fuel (green - solid) in the double swirler with syngas. The predicted operation range is indicated in red.

Pure fuels are mixed with diluents (steam) or introduced by pilot in a separate fuel injection. The challenge for fuel flexibility from very energetic fuels like H_2 and low LHV fuels like syngas is to maintain a high enough flow in the swirler while keeping pressure drops within specified limits. The pressure drops across the fuel and air swirler can be predicted for given ϕ and Ω at given T_{inlet} and power from the respective zeta values as shown in Figure 4.

The development strategy will further utilize a reduced combustor validation effort with sufficient modelling support to develop an operation concept for the plant for the variety of feed stocks and fuels as well as the transition between them. Further studies include turbulent combustion models and a deeper understanding of nitrogen chemistry in the reburn regime for the biofuel to mitigate NO_x formation from fuel bound nitrogen as well as tar production and consumption. The development will utilize literature studies, modelling and experimental testing at atmospheric and high-pressure conditions. Depending on the reburn performance as well as feedstock and the environmental permits, further post-combustion NO_x reduction techniques can be utilized, such as SCR.

The TopCycle Engine

The TopCycle is a novel steam-injected gas turbine at the heart of the BTC concept, first patented by Hansson (2006). Unlike other steam-injected gas turbines, steam injection is maximized to the boundary of near-stoichiometric combustion. This minimizes work for air compression and promotes a cycle with high working pressures to gain maximum work from the generated steam. Depending on scale and system optimization, intercooling is integrated to limit compression work of either spray (direct mixing) or boiling (convective) type.

The targeted efficiencies, when utilizing natural gas, are somewhat below combined cycle, but much higher power densities are achieved: 2-3 times kJ per mass inlet air, or 1.5-2 times higher kJ per volumetric flow of exhaust. Due to these factors, and the elimination of steam turbine, second generator and steam condenser, lower specific costs and a more compact plant result, making the TopCycle suited to mid-sized power plant markets.

Gas Turbine Architecture

The TopCycle requires a unique engine to manage relatively high-pressure ratios (20-40) at mid-scale (10-100 MWe). The main design challenges and their general solutions are shown below;

Table 3: Characteristics of the Top Cycle and corresponding engine features.

Near-stoichiometric combustion	Variable geometry to control air flow independent of fuel flow.
High volume flows in syngas and steam to combustor	Large fuel system and new combustor technology (see PACS).
Large volumes between the compressor and turbine	No power turbines. High operability margins for compressors.
High pressure ratio and flow mismatch of the compressor and turbine	Multiple shaft arrangements and/or high AN2* capability of turbine last stage.
High steam environment in the turbine	Effective cooling by either cool, humid air, 3D printed parts or steam cooling in open-loop (TE exit) configuration.
Development costs should be constrained.	Capability to re-use existing designs (parts or modules). Capability to uprate the engine.

*) Industry measure indicating turbine capacity, efficiency, and mechanical challenges.

Several different gas turbine architectures were investigated with respect to their complexity, operability, uprating capability, and development requirements. The most promising concepts have been developed further in a concept design phase where 1D analysis of the turbomachinery and cooling has been done in conjunction with process optimization prior to development work with a gas turbine OEM.

Gas Turbine Manufacturer

Phoenix has been intensively collaborating with Zorya Mashproekt, Ukraine on the gas turbine design and integration in the BTC plant. A concept study has been completed for two engine sizes for the entry-level BTC product. With their extensive experience in gas turbines and gearboxes for naval, oil & gas and power generation, including the Aquarius series featuring steam injection and water recovery, they have proven design, manufacturing, and fleet experience to address the challenges of a Top Cycle engine.

Flue Gas System

Heat Recovery Steam Generator

A forced circulation, single-pressure HRSG is foreseen consisting of an Economizer, Evaporator (drum type) and Superheater section. A very compact unit is obtained as little superheat is required and a relatively high gas exit temperature is needed to avoid the acid dew point and cold end corrosion. To ensure margin to the latter, the deaerator is set at a relatively high pressure to ensure a high inlet water temperature to the economizer. Saturated water can be let-down to generate the deaeration steam, rather than introducing an LP steam section. Fast-start features, similar to the Cheng Cycle ones (Macchi 1994), will be implemented to allow fast ramping of the HRSG and engine with secondary fuels to full load.

If mitigation of NOx from FBN in the combustion process proves insufficient, an SCR can be added at reasonable cost in the HRSG (upstream of the Evaporator). Any ammonia slip will be mostly captured in the flue gas condenser.

Flue Gas Condenser and Heat Rejection

Due to the BTC design philosophy, the flue gas dew point is normally above 80°C, allowing efficient water and heat recovery or heat rejection. Flue gas condensers (FGC) are utilized broadly in the Nordic region for this purpose in conjunction with biomass plants, with applications over 90 MW condensing duty found (Radscan 2023). In CHP applications, the condenser is the main heat supply, utilizing the latent heat from both injected steam and the water vapour formed in combustion. Utilizing the latent heat of steam allows high total efficiencies, i.e. efficiencies up to 110% on LHV basis, or 95% on HHV basis. Furthermore, flue gas condenser removes most remaining particulates and can be configured for sulfur removal.

Where heat is not utilized, conventional coolers are required to reject the heat from the FGC. By reducing the temperature to 50-55°C, sufficient condensate is recovered to eliminate ground water supply, depending on fuel type. This means air-cooled condensers can be used in most applications, again avoiding surface or ground water use. Note that electrical efficiency of TopCycle is therefore largely de-coupled from design of cooling tower, in contrast to a CCGT plant. Cooling the flue gas beyond 55°C and storing treated condensate, ensures operation robust to ambient temperature fluctuations.

Condensate Treatment

A key area in the plant, from a cost, reliability, and environmental perspective, is the treatment and recycling of condensate from the flue gas condenser to the steam/water cycle. Condensate from FGC installed for biomass boilers is often upgraded to demineralized water for boiler makeup (Teppler 2017). With gas turbine inlet air filter and the hot gas filter on the syngas, the flue gas quality, and therefore the condensate quality from the FGC, will be considerably better than in modern biomass plants and condensate treatment is not considered a risk. Rather, the boiler feed water and steam treatment must be designed to secure steam quality to the gas turbine, in particular alkali compounds, while still managing corrosion in the HRSG and the quality of any effluent flows to the environment. Previous installations with steam-injected or Cheng cycle installations have shown appropriate water and steam treatment designs.

BTC PLANT PERFORMANCE

The electrical efficiency of the BTC plant at the design point is reliant on many key factors. Careful consideration must be given to the turbomachinery performance at small flows and high pressure-ratios, the feasible conditions for reliable combustion, losses due to the engine architecture, correct exhaust temperatures to avoid cold end corrosion, and finally the cooling consumption. Table 4 presents a general overview of reasonable values to assume when simulating the BTC plant performance.

Figure 5 shows a theoretical performance map for the BTC concept. This has been generated for illustrative purposes with constant component efficiencies for a 100 MW_e scale plant. A practical performance map must be done in iteration with the capability of the engine manufacturer in question to capture correct trade-offs arising from, e.g. pressure ratio and compressor efficiency, cooling technology level, etc. Nevertheless, Figure 5 is useful to pinpoint some fundamental thermodynamic trends. First, the efficiency of the plant is very strongly affected by combustor outlet temperature, while pressure has a weaker but still significant influence with a large impact on the power density as well (for reference, a modern combined cycle is typically at 220 kJ/m3 exhaust gas). An increased working pressure also enables regions of higher firing temperatures due to the interplay of higher compressor discharge temperatures with the stoichiometric combustion process. This can also be obtained with less intercooling. High combustor outlet temperatures, 1450°C and above, are also favoured at high pressures as less steam is available from the exhaust. In summary, the fundamentals of BTC thermodynamics drive the design point to high pressures, which then allow higher firing temperatures. In practice, however, the trade-off with component efficiencies, cooling requirements and scale will limit the pressure, temperature, and efficiency.

Table 4: Typical assumptions for thermodynamic performance calculations.

Ambient	ISO (15°C, 1.103 bar)
Feedstock	Forest residue, see Table 1
Biomass moisture contents - raw and after dryer	50 % - 15 %
Carbon conversion in gasifier	98 %
Hot gas filter temperature	400-500°C
Compressor polytropic efficiency	84-89 %
Turbine stage isentropic efficiency	87-92 %
Gearbox efficiency	98%
Generator efficiency	98%
Turbine inlet pressure	20-45 bar
Combustor outlet temperature	1200 – 1400 °C
Intercooler pressure	5 - 15
Heat exchanger pinches	3-12°C
ECO gas outlet temperature	90-140°C

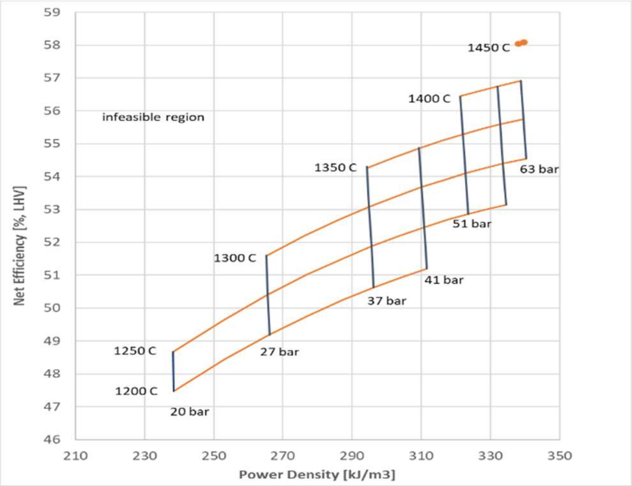

Figure 5: Illustrative performance map with optimized assumptions at 100 MW scale.

APPLICATIONS FOR BTC AND TOPCYCLE IN A DECARBONISED ENERGY SYSTEM

BTC expected product range in power and heat markets goes between 10 and 100 MW electric power capacity with 10, 40 and 100 MWe units judged most suitable to capture the growing biopower market and other mid-sized applications. The engines are foreseen to be introduced with lower ratings and the capability to develop to high pressures and firing temperatures, and to include better technologies, e.g. for cooling.

Table 5: Targets for BTC performance. P10, P40, P100 are standardized plants for 10, 40, 100 MWe capacity.

		P10	P40	P100
Launch el. efficiency	(%, LHV)	40%	47%	50%
Mature el. efficiency	(%, LHV)	44%	51%	54%
Mature with BECCS	(%, LHV)	36%	43%	46%
Working pressure	bar	20-24	28-33	35-40
Combustor outlet temperature	K	1450+	1500+	1600+
Cooling technology		Humid air	Humid air	Steam

In Table 5, the target performance of the BTC family is presented, including the data for a first generation (Launch) that can be uprated to a mature variant of the engine and their respective core technology levels. The targets include considerations of component performance at pressure and impact of the cooling technology.

Utilizing local waste streams of biomass at prices 10-25 €/MWh, marginal electricity production costs are limited to 25-75 €/MWh, depending on the plant size and maturity. This is sufficient to dispatch into the EU electricity market compared to natural gas combined cycles with current and future CO_2 emission costs. If a fast dispatch is required, hydrogen or methane can be utilized, and then the switch to biomass can cover longer periods at much lower operating costs.

Economics are further improved when addressing additional value streams for the plant. The following sections will briefly discuss two important examples; the BTC in district heating and the BTC combined with CCS.

District Heating

Given that a BTC plant can supply large quantities of heat at 75 - 80°C, with negligible penalties from the power cycle, and is therefore well-suited to so-called 4th generation district heating systems in the Nordics and new-built areas. Measures are required to utilize this heat in older grids e.g. heat pumps, supplementary firing, or serial connection to other plants.

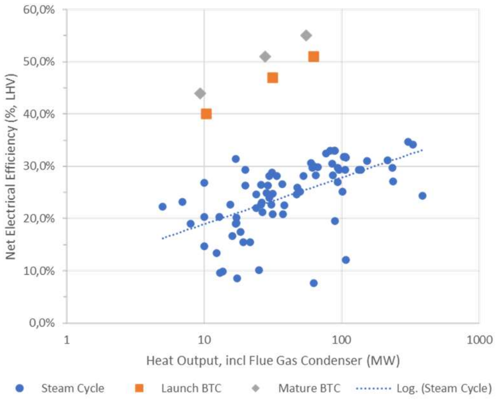

Figure 6: Electrical efficiency of biomass-fired CHP plants for a given district heat supply.

Within the EU there is well over 900 TWh of district heating consumption that is predominantly driven with fossil fuels and must be decarbonized (Szabó 2015). Further, many countries are introducing local and district heating, e.g. UK, France. Figure 6 shows the electrical efficiency of BTC compared to the installed base of CHP plants in Sweden. Classical biomass CHP plants have an electrical yield (power to heat ratio) of 0.35, including the FGC, while BTC has a ratio of 1-1.4. Therefore, the amount of electricity from CHP can be raised by up to a factor 4. This production is close to consumption, something critical when transmission and distribution grids are a severe bottleneck in electrification efforts.

BTC targets a more profitable CHP plant while also providing significant local capacity. The marginal cost of heat supply for a 10 MWe BTC plant with 20 €/MWh biomass even becomes negative when electricity prices are above 40-50 €/MWh, depending on the electric yield, while Rankine cycles require electricity prices at 75-120 €/MWh for the same result. This conclusion is obtained simply by dividing the fuel cost with the heat efficiency (20/0.4) and subtracting the electricity price times the electrical yield (50*1.2).

Carbon Dioxide Removals (BECCS)

Phoenix is now in the second phase of a feasibility study with Drax Power Station, the world's largest operator of biopower plants, with the objective to increase the profitability and efficiency of co-producing negative emissions and electricity. Carbon dioxide removals are an emerging market where negative emissions, formed when sequestering biogenic carbon, will be traded at comparable or even higher prices than fossil CO_2 emissions (e.g. ETS). Trading schemes for carbon offsets and similar mechanisms will greatly help the business case of this technology. As an example, if 1 ton CO_2 is removed per MWh_e, e.g. for the P40, a CO_2 removal income of 100€/ton gives a credit of 100 €/MWh_e, again decreasing marginal costs and allowing dispatch into the market.

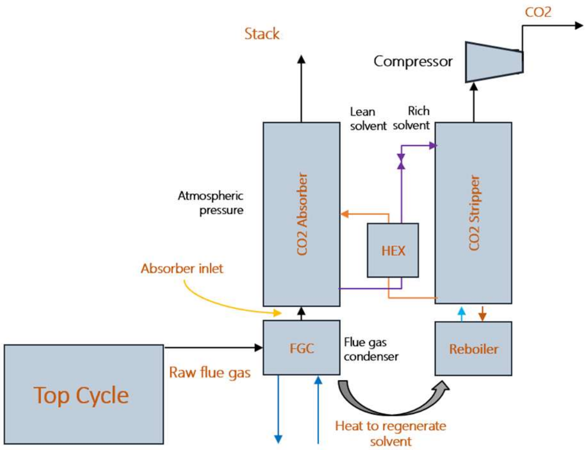

Figure 7: Absorption type CO_2 capture concept for BTC

A benefit of near-stoichiometric combustion in BTC is that CO_2 concentrations are maximized in the exhaust, together with low O_2 levels, both crucial parameters for cost-efficient CO_2 capture. A post-combustion capture plant can be driven efficiently by waste heat from the flue gas condenser, limiting energy penalties to primarily auxiliaries, CO_2 compression and if applicable liquefaction, see Figure 7. In case available heat is not at sufficient temperature for the reboiler in the capture unit, a heat pump can be installed to upgrade the heat. With some capture technologies, CHP operation is possible, i.e., most of the energy used to drive the capture process can then be utilized for district heating in 4th generation grids, but at the expense of a higher electricity penalty. For many cases, however, a BTC-CCS plant will become primarily a power-gen plant with CO2 as byproduct. In the Drax pre-study, major CO_2 capture unit providers have participated with standardized and optimized solutions. From these solid investigations it was found that BECCS is possible with only 8-10% point reduction in efficiency, or a 16-20% loss in capacity, which is much lower than boiler plants at 30-37% (Lehvin 2019). This significantly changes the economics of CO_2 capture and 50-100% more electricity is generated than boilers for the same biomass. This allows the delivery of both renewable electricity and carbon dioxide removals at lower electricity costs.

DEVELOPMENT PATHWAY

Given the above description of the process steps, the key development challenges addressed in BTC can be summarized as follows:

- Reliable biomass gasification with fuel flexibility and operability.
- Combustion of steam-diluted product gas with minimum excess air and high fuel flexibility.
- Novel gas turbine design with high steam injection
- System integration, plant design and dynamics.

Phoenix Biopower has launched a development program to push these areas through the early TRL scale and enable a full-scale demonstration plant for the 10 MW class in a phased effort. Development is currently focused on component level testing, utilizing scaled rig environments and simulations to develop the concepts and designs needed.

The burner validation and combustor development is ongoing at the atmospheric rig in Stockholm, which allows to test with variants up to 200kW. As a "fuel to flame" configuration it is operating on the real syngas from an atmospheric biomass gasifier using a variety of feedstocks. The combustor can switch between syngas and gaseous fuels blends including i.e. LPG, CH_4 and H_2 and optimize different operation points and transients. In this rig not only combustion performance, the cooling designs and operation can be tested, but also the interplay of the gasification and combustion system at steady and at transient points.

First results from a fuel to flame rig in Stockholm are presented in Figure 8. The rig is equipped with full emission analysis, pressure readings and thermocouples. The very recent data here are limited to flame images of mixed operation with syngas and propane. More data and detailed analysis will be presented later. The highly diluted MILD flame without LPG is stable but barely visible at low power. Also, the mixed flame indicates a broadly distributed heat release zone.

The burner variants and cooling concepts are tested at medium pressures at the new test rig at TU Berlin. 1 MW of thermal power can be used at pressures of up to 10 bar with high steam dilution or at 300 kW per bar and burner at a total of 3 bar. The engine combustor combines several cans with slightly upscaled burners to fit the requirements.

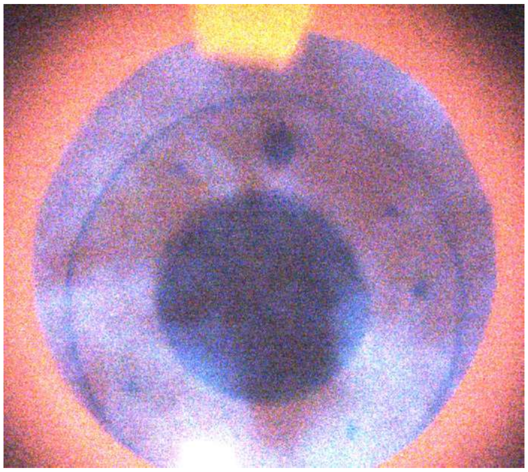

Figure 8: Flame image from a "fuel to flame" rig in mixed operation bio-syngas and propane.

A pilot-scale cold-flow rig has been designed and constructed to validate the fluidization concept of the gasification system at high pressure through measuring hydrodynamic characteristics of the dissimilar fuel and bed particles circulation and mixing. The rig can provide inputs and validation data for developing a CFD tool. The CFD model also incorporates reaction kinetics from pressurized TGA tests and can be validated at hot status using experimental inputs at the pressurized fluidized bed rig at KTH.

High-pressure gasification performance is conducted at pressures up to 40 bar at KTH to obtain products gas characteristics data, e.g. main gas compositions, release of Cl, N, and K-containing species, and investigate the effect of main process variants including, i.e. pressure, bed materials, feedstock, temperature, steam injection.

COMMERCIALISATION AND DEMO PLANT

Utilizing three standard sizes in the mid-size range, the BTC products aim to capture both the existing markets and growth for larger biopower plants with BECCS. The engine is also suitable for distributed applications with hydrogen. Phoenix BioPower aims to commercialize the BTC technology through establishing a semi-commercial demonstration plant at 10 MW_e scale, see Figure 9. The 10 MW_e class was chosen to limit development costs while still addressing large biomass market segments.

The demonstration project shall be executed by a consortium of utilities and suppliers, including Phoenix and the gas turbine manufacturer. To manage risks, a phased approach to commissioning is utilized, with the Gasification System commissioned in phase 1 at low pressures and capacity with a modified conventional gas turbine. In phase 2, the new Top Cycle unit is delivered, and full pressure and capacity operations will then be demonstrated by the latter part of this decade. Through executing the previously outlined development projects along with pre-studies with multiple utilities, work is progressing at pace to realize this target.

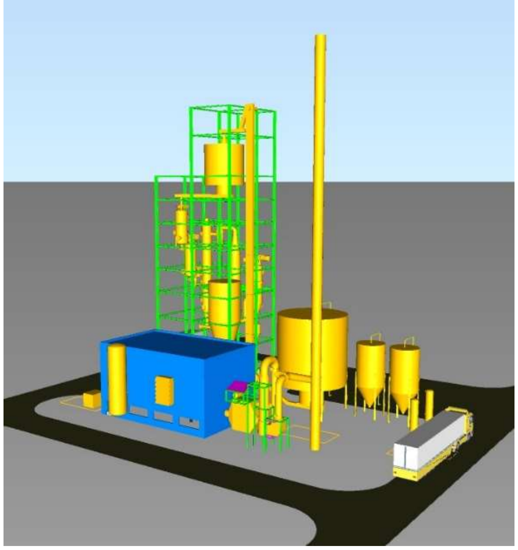

Figure 9: 3D layout of the 10 MWe BTC demonstration plant. Gasification system in the green structure, gas turbine in the blue building with HRSG and FGC upstream the stack.

CONCLUSIONS

Phoenix BioPower is developing a new solution for the decarbonized energy system that offers cost-effective and dispatchable renewable power. The TopCycle can be utilized for high efficiency biopower with significantly lower marginal cost of electricity than conventional fossil and biopower alternatives. Promising applications are CHP and BECCS, along with hydrogen utilization.

Development work is progressing through the concept stage with good results for tests at TRL 3-5. These show that the overall requirements of the plant can be met with careful component design and integration. Testing at scale is a prerequisite of verifying design tools and laying a platform for scaling-up. The main risks currently being addressed are in combustion, gasification, gas turbine engine design and plant integration. A 10 MW BTC demonstration plant, executed by a consortium of suppliers and utilities, is now in a feasibility phase with the target to realize high-efficiency and fuel-flexible renewable electricity production before 2030.

ACKNOWLEDGEMENTS

Phoenix BioPower gratefully acknowledges the support and public grants to launch this development effort from the Swedish Energy Agency, CINEA, and Vinnova. Further the support of InnoEnergy has been critical. Valuable insights and input have been provided by our Reference Group (Tekniska verken i Linköping, Stockholm Exergi, Sveaskog, Svenska Kraftnät, SSAB, is also gratefully acknowledged. Phoenix BioPower development work builds upon previous work conducted by Euroturbine, Vattenfall and MTU Aero Engines. Finally, funding is gratefully received also from EU projects BioFlexGen and EUCanWin!

REFERENCES

AndréFaaij, Renévan Ree,LarsWaldheim, et.al. «Gasification of biomass wastes and residues for electricity production.» *Biomass and Bioenergy* 12: (1997): 387-407.

Blouch, J., Li, H., Mueller, M., and Hook, R.,. «Fuel Flexibility in LM2500 and LM6000 Dry Low Emission Engines.» *ASME Paper* , 2011: GT2011-45387.

Cavaliere, A., and de Joannon, M. «Mild combustion.» *Prog. Energy Combust. Sci.*, 2004: 329–366.

De Joannon, M., et al.,. *Combustion Science and Technology*, n° 153, (2000): 33.

E. Rocca, L. Aranda, M. Molière. «Chemistry of Ash-Deposits on Gas Turbines Hot Parts: Reactivity of Nickel, Zinc and Iron Oxides in (Na, V, S) Molten Salts.» *Materials Science Forum* . 2008.

E.Simeone, M. Siedlecki, M.Nacken, et al. «High temperature gas filtration with ceramic candles and ashes characterisation during steam-oxygen blown gasification of biomass.» *Fuel* 108 (2013): 99-111.

Elforsk. *El från nya och framtida anläggningar.* Elforsk, 2014.

Elkady, E., et al. *ASME Turbo Expo*, 2011: GT2011-46482.

ERC, NL. *E. Efficiency. 2015 Phyllis2-Database for biomass and waste.* 2015. https://phyllis.nl/.

Phyllis2-*Database for biomass and waste. page,.* s.d. https://phyllis.nl/.

ETN, Hydrogen Combustion working group of. «Addressing the combustion challenges of hydrogen addition to natural gas.» *European Turbine Network*, 2022: white paper.

F. Guethe, D. Stankovic, F. Genin, K. Syed, D. Winkler. «Flue Gas Recirculation of the Alstom Sequential Gas Turbine Combustor Tested at high Pressure.» *ASME Turbo Expo*, 2011: ,GT2011-45379.

F. Güthe, M. de la Cruz García, A. Burdet. «Flue gas recirculation in gas turbine applications: investigation of the chemical reactivity and NOx emissions.» *ASME Turbo Expo.* 2009. GT2009-59221.

Frida Jones, Mattias Bisaillon, Daniel Lindberg, Mikko Hupa. «The presence of zinc in Swedish waste fuels.» *Waste Management* 33 (2013): :2675-2679.

IEA. *Bioenergy's role in balancing the electricity.* Task 41P6: 2017: 01, IEA, 2017.

IIkka Hanula, Esa Kurkela. «A parametric modelling study for pressurised steam/O2-blown fluidised-bed gasification of wood with catalytic reforming.» *Biomass and Bioenergy* 38 (2012): 58-67.

IPCC. *Global Warming of 1.5 ℃-An IPCC special report.* IPCC, 2018.

IRENA. «Global Renewables Outlook: Energy transformation 2050.» IRENA, 2020.

J. Blouch, H. Li, M. Mueller, and R. Hook,. «Fuel Flexibility in LM2500 and LM6000 Dry Low Emission Engines.» *ASME Turbo Expo*, 2011: GT2011-45387.

J.Krook, A. Mårtensson, M. Eklund. «Metal contamination in recovered waste wood used as energy source in Sweden.» *Resources Conservation & Recycling* 41 (2004): 1-14.

Jones F., Bisaillon M., Lindberg D., Hupa M. «The presence of zinc in Swedish waste fuels.» *Waste Management 33*, 2013: 2675-2679.

K. J. Wisniewski, S. Handelsman. «"Expanding Fuel Flexibility Capability in GE's Aeroderivative Engines.» *ASME Turbo Expo*, 2011: GT2011-45387.

K. Zhang, S. Dybe, Y. Shen, M. Bartlett, S. Schimek, C. O. Paschereit, C. Duwig. «Experimental and numerical investigation of ultra-wet methane Combustion technique for power generation.» *ASME Turbo Expo*, 2020: GT2020-15163.

K.Salo, A.Horvath, J.Patel. «Pressurized gasification of biomass.» *ASME GT-349.* 1998.

Krister Ståhl, Lars Waldheim, Michael Morris, Ulf Johnsson and Lennart Gårdmark. «Biomass IGCC at Värnamo, Sweden-Past and Future.» *GCEP Energy Workshop.* 2004.

Lehvin, F., Linde L., Gustafsson, K., Dahlen, E. *Introducing BECCS through HPC to the research agenda: the case of combined heat and power in Stockholm.* Energy Reports 5, 2019.

Li, P., Mi, J., Dally, B.B. et al. . «Progress and recent trend in MILD combustion.» 2011. 255–269.

Lieuwen, T., Mcdonell, V., Santavicca, D., and Sattelmayer, T. «Burner Development and Operability Issues Associated With Steady Flowing Syngas Fired Combustors.» *Combust. Sci. Technol.,* 180 (2008): 1169.

Lindståhl, Henrik. *RT-FLIS, STUDIE AV KEMISK SAMMANSÄTTNING.* . Report from Tekniska Verken., s.d.

Lomax, G., Workman, M., Lenton, T., Shah, N. *Reframing the policy approach to greenhouse gas removal technologies.* Energy Policy 78, 125–136, 2015.

Macchi, E, & Poggio, A. "A Cogeneration Plant Based on a Steam Injection Gas Turbine With Recovery of the Water Injected: Design Criteria and Initial Operating Experience." 94-GT-017 Congress Proceedings of the ASME 1994 International Gas Turbine and Aeroengine and Exposition.M. Zajadatz, F. Güthe, E. Freitag, T. Providakis, T. Wind, and F. Magni, J. Goldmeer. «Extended Range of Fuel Capability for GT13E2 AEV Burner with Liquid and Gaseous Fuels", ASME Turbo Expo, GT2018-76374, (2018).» *J. Eng. Gas Turbines Power*, 2018: GTP-18-1441.

Nils Skoglund, Linda Bäfver, Johan Fahlström, Erik Holmen, Caroline Renström. «Fuel design in co-combustion of demolition wood chips and municipal sewage sludge.» *Fuel Processing Technology* 141 (2016): 196-201.

P. Kuhn, S. Terhaar, T. G. Reichel und C. O. Paschereit. «Design and Assessment of a Fuel-Flexible Low Emission Combustor for Dry and Steam-Diluted Conditions.» *Proceedings of ASME Turbo Expo 2015*, 2015: GT2015-43375 .

P. Stathopoulos, P. Kuhn, J. Wendler, T. Tanneberger, S. Terhaar, C. O. Paschereit, C. Schmalhofer, P. Griebel und M. Aigner. «Emissions of a wet premixed flame of natural gas and a mixture with hydrogen at high pressure.» *Journal of Engineering for Gas Turbines and Power*, 2016: 139.

P.StåhIberg, E.Kurkela and. «Air gasification of peat, wood and brown coal in a pressurized fluidized-bed reactor. I. Carbon conversion, gas yields and tar formation.» *Fuel Processing technology* 31 (1992): 1-21.

Palulli, R., et al. «Characterisation of non-premixed, swirl-stabilized, wet hydrogen/air flame using large eddy simulation.» *Fuel*, 2023: submitted.

Radscan home page. 2023. https://www.radscan.se/SE/referenser.

Raslan A., Yang S., Durocher A. and Bergthorson J.M. , Güthe F. «NOx emission characterization of ammonia containing humidified syngas using Chemical Reactor Modelling in

Rich Quench Lean (RQL) combustion.» *Proceedings of Combustion Institute - Canadian Section, Spring Technical Meeting*, 2023: submitted.

Rocca E., Aranda L., Molière M. «Chemistry of Ash-Deposits on Gas Turbines Hot Parts: Reactivity of Nickel, Zinc and Iron Oxides in (Na, V, S) Molten Salts.» *Materials Science Forum*, 2008: 595–598:169–76.

S. Dybe, F. Güthe, M. Bartlett, P. Stathopoulos, C. O. Paschereit. «Experimental Characterization of the Combustion in Fuel Flexible Humid Power Cycles.» *ASME Turbo Expo*, 2021: GT2021-58675.

S. Dybe, M. Yasir, F. Güthe, R. Alemela, M. Bartlett, B. Schuermanns, C. O. Paschereit. «On the Demonstration of a humid Combustion System Performing flexible Fuel-Switch from pure Hydrogen to Natural Gas with Ultra-Low NOx Emissions.» *ASME TURBO EXPO*, 2023: GT2023-103023.

S. Göke, S. Schimek, S. Terhaar, T. Reichel, K. Göckeler, O. Krüger, J. Fleck, P. Griebel, C. O. Paschereit. «Influence of Pressure and Steam Dilution on NOx and CO Emissions in a Premixed Natural Gas Flame".» *J. Eng. Gas Turbines Power*, 2014: 136.

Seán T.Mac an Bhaird, EilínWalsh, PhilHemmingway, et al. «Analysis of bed agglomeration during gasification of wheat straw in a bubbling fluidised bed gasifier using mullite as bed material.» *Powder Technology* 254 (2014): 448-459.

T. Wind, F. Güthe, K. Syed. «Co-Firing Of Hydrogen And Natural Gases In Lean Premixed Conventional And Reheat Burners (Alstom GT26).» *ASME Turbo Expo*, 2014: GT2014-25813.

Teppler, M., Wood, J., Buzzell, B. «Flue gas condensate and energy recovery.» *78th Annual International Water Conference 2017, IWC-08-17.* 2017.

Yang, S., A. Raslan, A. Durocher, F. Guethe, et J. Bergthorson. «Numerical Investigation of NH3 Doped Fuels from Biomass Gasification on fuel-bound NOx Formation at Gas Turbine Conditions,.» *ASME Turbo Expo*, 2023: GT2023-103191.

Zhou C-W., Li Y., Burke U., Banyon C. , Somers, K.P., Khan S., Hargis J.W. , Sikes T., Petersen E.L., AlAbbad M. , Farooq A., Pan Y., Zhang Y., Huang Z., Lopez J. ,Loparo Z. , Vasu, S.S., Curran H.J. «An experimental and chemical kinetic modeling study of 1,3-butadiene combustion: Ignition delay time and laminar flame speed measurements.» *Combustion and Flame* 197 (2018): 423-438.