FOUNDATIONS

Final Report to Swedish Energy Agency

Phoenix Biopower

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Sammanfattning

Behovet av lokal, planeringsbar, förnybar energi har ökat dramatiskt. Beroendet av fossila bränslen hotar tryggheten i energiförsörjningen, orsakar klimatförändringar och är dyrt. Den kraftiga tillväxten av intermittenta förnybara energikällor kan effektivt kompletteras med BTC-tekniken (Biomass-fired Top Cycle), vilken flexibelt och robust kan utnyttja hållbar och lokalt framställd biomassa med en elverkningsgrad på upp till 50%.

Projektet FOUNDATIONS har levererat flera betydande resultat för att lägga grunden för kommersialisering och möjliggöra marknadsinträde för den nya BTC-tekniken. I synnerhet har en första standard 10 MW BTC-produkt definierats och alla tekniska koncept identifierats med Zorya-Mashpoekt, en ukrainsk gasturbintillverkare. Vidare har affärsplanen och den kommersiella färdplanen uppdaterats, inklusive en demonstrationsanläggning. Slutligen gjordes en förstudie av demonstrationsanläggningen och en skiss för pilot- och demoprogrammet utvecklades.

Summary

The need for local, plannable, renewable power has risen dramatically. Reliance on fossil fuels threatens energy security, causes climate change and is expensive. Growing amounts of intermittent renewables can be efficiently complemented with the novel Biomass-fired Top Cycle (BTC) technology, which can flexibly and robustly utilise sustainable and locally sourced biomass at electrical efficiencies up to 50%.

The project FOUNDATIONS has delivered several significant results to lay the foundations for commercialisation and enable the market-entry of the novel BTC technology. In particular, a first standard 10 MW BTC product has been defined and all technology concepts identified with Zorya-Mashpoekt, a Ukrainian gas turbine manufacturer. Further, the business plan and commercial roadmap has been updated, including a demonstration plant with phased management of risk. Lastly, a pre-feasibility study of the demonstration plant was made and a sketch for the Pilot & Demo programme was developed and submitted.

1 Introduction and Background

The energy transition to a renewable, sustainable and fossil-free energy system has begun globally and must be accelerated in order to reach both national and international goals and agreements. Since 2017, Phoenix BioPower has successfully driven the development of a ground-breaking, highly efficient technology for combined heat and power production (CHP) from biomass residues, the so-called BTC technology. The innovation builds on Swedish traditions in gas turbine, biomass gasification and CHP technologies, and results in a unique increase in performance to 45–55% electrical efficiency, compared to today's 25–34%. The BTC addresses many of the challenges facing Sweden and the world when the energy system is to be converted to a renewable one by offering large volumes of cost-competitive, flexible, renewable, and local power and heat generation.

High electrical efficiencies are achieved by the BTC plant through integrating a biomass gasifier and gas turbine at high pressure and recovering waste heat with steam, which is injected in the gas turbine. The central concept is thus to minimize the amount of excess air, and therefore air compression, in the gas turbine and thereby to maximize the generator output. This results in cost-effective electricity generation through high electricity and total efficiencies, even in bio-CCS. As the ratio of power to heat is tripled, up to 3 times more electricity can be produced from the same district heating network compared to today's technology.

To develop the combustion, gasification and plant technology, Phoenix cooperates with several prominent institutions in Europe, such as RI.SE, KTH and TU Berlin. A reference group and large power companies such as Stockholm Exergi and Drax Group are working with Phoenix to support development and commercialization. Many additional actors contribute to two Horizon 2020 projects; Bio-FlexGen and EUCANwin! where technology will be validated at TRL4/TRL5 for flexible CHP, H2- firing and syngas production for H2 synthesis. A Eurostar project, PACS2020; complements these projects within combustion design, testing and commercialization. Earlier projects with the Swedish Energy Agency have looked at basic technology feasibility (Phase 1 completed in 2019), component development (Phase 2, ended May 2022) as well as a BTC Pilot Plant feasibility study together with TvAB in Linköping (completed in 2021).

Together with partners, approximately SEK 90 million has been invested in the development of BTC technology since 2017. Phoenix currently has 16 employees and employs another 6-10 externally. The patent portfolio is continuously evolving and currently includes 39 granted patents in 9 patent families, with two pending and additional patent applications under development.

A consortium of companies will be needed to commercialize the BTC technology, specifically through a demonstration plant (operating in 2028–30), followed by international expansion. Phoenix' role is to develop and supply or license the gasification and combustion system along with plant integration. Therefore, the key remaining technology is the gas turbine, which also represents the largest investment in the development process and requires a large manufacturing and aftermarket capability.

Since 2020, Phoenix has been in in-depth discussions with a Ukrainian gas turbine manufacturer, Zorya-Mashpoekt (ZMT) with the aim of co-developing a gas turbine based on the company's patented BTC technology. A development project is now being conducted to develop the concept for the Top Cycle gas turbine in two different sizes 10-30 MWe. This technical work includes performance, 1D analysis of the turbine, engine architecture, integration of the Phoenix combustion

chamber and analysis of emergency cases. Work was paused for about two months due to Russia's invasion of Ukraine but resumed beginning on Good Friday.

This co-operation is very significant for the commercialisation effort; however, it also has obvious challenges not just given the current war, but also in terms of gas turbine technology levels, market presence and organisation/culture challenges. Significant work is needed to evaluate from multiple perspectives whether the ZMT engines are preferable to more modern suppliers such as Siemens, Kawasaki.

In conjunction to this evaluation, an update of the Phoenix business plan and strategy is needed, given the large shifts in the market resulting from, e.g., the Ukraine-Russia war, fossil fuel prices / increased pressures on energy system, the latest EU policy and regulations on bioenergy and hydrogen. Included in this is to develop and analyse the main scale-up steps required for the different suppliers, i.e., the pilot plant at 1-3 MWe and the demonstration plant at commercial scale (10-30 MWe). This project shall therefore update the business plan, commercialization and market strategy, including defining the Demo plant scope and subsequent Pilot plant scope.

2 Project Goal

FOUNDATIONS had three major goals

- Goal 1: Define the first standard BTC product for market introduction and associated gas turbine supplier. Choose the optimal plant size and gas turbine based on current work carried out together with Zorya-Mashpoekt as well as at least one further company with more modern gas turbine parameters.
- Goal 2: Update the business plan and commercial roadmap, including a demonstration plan, based on the standard BTC product, findings from from previous and parallel projects as well as market shifts the past 2-3 years, including the war in Ukraine.
- Goal 3: Prepare the basis for BTC Pilot Plant (tech concept incl. GT, and business case) and the partnership structure for 2023 application to Demo & Pilot programme.

2.1 Targeted results and outcome

The long-term goal of commercializing the BTC technology is to create a new Swedish export product that contributes significantly to the Swedish and global transition to sustainable energy systems. The execution of this project and the implementation of its results is a crucial part of the commercialisation. It will update and deepen the framework and basis for scale-up, therefore coupling successive technical results from ongoing and previous projects, to a final product that gives significant value creation and climate benefits in Sweden and abroad.

The project targeted the following exploitable results

- Optimised definition of the final BTC product, updated for the market developments, requirements, value and supplier capabilities
- Involvement of key end-users and gas turbine supplier in the coming scale-up projects to pilot and full-scale demonstration unit
- Actionable update to the Phoenix business plan including plans for market-entry, partnering, scale-up, financing and proposed commercial framework for first Demo plant
- Basis for the BTC Pilot Plant project and associated application to the Swedish Energy Agency call “Pilot & Demo Programme”

3 Definition of BTC product

Work with analysing the biomass market for the BTC and mapping it to the characteristics of the BTC are outlined in detail in the appendix, some of which is sensitive information for the company. This chapter therefore summarises some elements of the work and main findings.

3.1 Market analysis

The BTC product is designed for high-efficiency generation of electricity from local streams of biomass residues, giving also flexible operations and high performance while capturing biogenic CO2 from the flue gas. Three core markets have been identified to address:

1. Local, renewable electricity generation to i) replace fossil sources and ii) meet the growing need for electricity, globally. Fossil-free electricity is needed in large quantities to electrify our growing societies. BTC offers a radically higher electricity yield from local biomass streams, giving lower operating (fuel) costs for biomass power plants and CHP plants. Further, as a local plant, generating on regional grids, it will provide sufficiency and capacity on a decentralized level, and heat when district heating grids are available.
2. Flexible, renewable electricity generation as a complement to intermittent electricity from solar and wind power. The majority of growth in renewable electricity will be from intermittent solar and wind power, requiring different assets to assure sufficiency when they cannot operate. Currently, fossil power plants are utilized to provide this, and hydrogen fired plants are envisioned in the future. Flexible electricity production, however, from BTC can fill this segment at a much lower marginal cost than fossil fuels with ETS costs or hydrogen.
3. Bio-CCS is emerging as a key source of carbon dioxide removals (CDR), i.e. reducing atmospheric carbon dioxide levels rather than only decreasing fossil emissions. As the BTC can capture CO_2 while still producing 50-100% more electricity than conventional biomass power plants, CO_2 has a lower specific cost per unit captured.

Further information can be found in the prospectus which will be published in late May and in the Information Memorandum, published in November (and included as Appendix). Further, a comprehensive market study (included as Appendix) was conducted as part of the project and contains a global market overview and breakdown per type of fuel, application, region.

From this material, the launch application for BTC has been identified as follows

- Combined heat and power in district heating networks, with or without bio-CCS. Typical markets are Nordics, Central and Eastern Europe with larger plants in the Nordics (50-500 MW biomass) and smaller in the latter markets (20-100 MW). Local woody residues are feedstock in the first applications, but lower grade biomass will be utilised in follow-on plants, i.e. increasing fractions of demolition waste, certain agricultural residues. Supply of grid services and peaking power is done outside of heating season or in transition periods (spring/autumn) utilising secondary fuels (bio-oils, hydrogen, etc).

3.2 BTC engine size

As the BTC requires a specific gas turbine which is very costly to develop, it is necessary to have a standardised product size built around this engine, rather than tailoring every plant for each site. This means identification of the relevant engine size is a crucial decision.

A detailed market analysis (in the Appendix) found that an optimal portfolio has one engine at roughly 10-15 MWe and one at 35-40 MWe engine to avoid cannibalisation and cover as much of

total volume in the existing biopower market as possible with these two sizes. Further, the expansion of biopower in large industrialised Asian markets (Japan, South Korea) and for CHP plants in European cities is with plants over 200 MW fuel, which may motivate a 100 MWe BTC product to gain maximum economies of scale and plant performance.

Looking at Total Available Market regarding new-build plants for a portfolio of BTC engines we find that it is in the order of 100B€/a at 3.4GWe/a. With an assumed share of 10% of new plants, this represents a potential of 10B€/a or 30 - 300 units/a depending on the mix of plant sizes. The full market potential is expected to be reached within 10 - 15 years of commissioning of the first commercial plant and assuming a new size is commercialized within 10 years of the first plant.

3.3 BTC engine performance and competitiveness

Developing the BTC plant with an engine based on Zorya Mashproekt current technology levels gives a plant performance below the original targets for the BTC plant. For the 10 MWe plant, a span of 38-42% is found for the market-entry engine, depending on the type of biomass and operating conditions. With successive improvements to the engine, this should improve to 42-45%, well above the rankine cycles (15-27% for that scale boiler) and above gasifiers with ICE (25-35%). Long-term competitors with combined cycle systems are unlikely due to the small plant scale. Therefore, the Zorya engines are concluded to be suitable for the 10 MW BTC plant.

The competitiveness of the BTC compared to conventional plants has been examined. The levelized cost of the BTC plants are typically 20-50% lower than competitors. Absolute LCOE are from 80-120 €/MWh in a EU market setting for the smaller plants, depending on application and technology level of the gas turbine. The BTC can be favourably used in power-only or district heat applications. Achieving 100 €/MWh is considered unique for year-round local, renewable electricity generation at this scale. However, the BTC at 10 MWe can probably not be commercially built to compete on the open commodities market. While high operating hours will be achieved due to low fuel costs, the margins are insufficient to pay back the investment. Therefore, a PPA or other commercial mechanism is needed with local actors who value the (currently) non-monetary values of local production is needed. Alternatively, a subsidy mechanism from governments are needed for power-only operation, particularly on the investment cost.

The Appendix includes details about the LCOE for different engines.

4 Updated Business plan

4.1 Definition of the BTC Demo Plant

A major outcome of this study was the decision to progress to a 10-11 MWe demonstration plant as both a technology demonstration but also to launch the first full-scale BTC product. Furthermore, it was found that the optimal pathway to execute the entire development and commercialisation project is to incorporate two phases in the Demonstration Project at the same plant, rather than building a separate pilot plant first to mitigate risk at lower scale and then the 11 MWe plant. As the BTC technology is pressurised, the capacity is essentially a factor of pressure, if the geometry is kept constant. The difference in pressure at low and high capacity is not a significant enough risk to motivate two separate plants where the pilot is at full pressure. Such a requirement would also exclude utilising a small, conventional gas turbine to demonstrate the BTC process.

See Section 5 for more details and the Appendix for the project sketch submitted to the Energy Agency as a result of this work.

4.2 Business plan update

During the project FOUNDATIONS, the business plan was updated twice to reflect the major findings. First, to account for the market assessment and product portfolio identified. Second, to account for the new definition of the demonstration plant and project. The former was included in an Investment Memorandum (appendix) published in November 2022. The latter is included in a prospectus submitted to Finansinspektionen in March 2023.

These include the dimensions of market, technology, development roadmap and projects, consortium, business model and financing.

4.3 Engagement of the Gas Turbine Suppliers

The key partner for the commercialisation of BTC platform is the gas turbine. These systems are cost-intensive to develop over long periods of time and, in some cases, utilise very high technology level that few companies can offer.

Project FOUNDATIONS has allowed continued work with Zorya Mashproekt to develop the concept engineering of the 10 and 25 MWe scale Top Cycle gas turbine engines. The 10 MWe engine is the basis for the demonstration plant project that is outlined in Section 5 and the sketch submitted to the Energy Agency.

In parallel, new designs with more advanced design conditions have been developed for a 40 MW and 100 MW plant. These will be used in further discussions with the industry.

5 Basis for pilot plant project

During FOUNDATIONS, a pre-study of the pilot plant project was made, with the crucial decision to integrate it into the first phase of the demonstration plant. The full project outline, including assessment of goals, cost, schedule, work package descriptions, partners, financing, commercial frameworks, etc, can be found in the application sketch, submitted to the Pilot & Demo Program, which is attached as an appendix to this report.

In the BTC Demonstration project, the BTC technology will be demonstrated for the first time with a semi-commercial 11 MWe plant. The overall goal is to demonstrate the conversion of low-grade biomass to electricity using the BTC technology on a full scale. This will enable BTC's entry into the market and a rollout of the technology in Sweden and globally. The overall goal is to be achieved in two phases with the same facility, i.e:

- Phase 1: demonstrate the integrated BTC process operating at low pressures (9-11 bar) and with a modified conventional 2.5 MWe gas turbine.
- Phase 2: demonstrate the performance and operation of the BTC process at full capacity and pressure with a newly developed 11 MWe Top Cycle gas turbine.

In more detail, the objectives are:

- To evaluate the BTC plants' function, i.e. operating characteristics, environmental data, fuel flexibility with solid biomass and gaseous fuels, system solutions and evaluating the function and performance of individual components.
- To propose and make modifications to the system and components to achieve set functional and environmental requirements with good availability and economy for future facilities.
- To validate and update the documentation, know-how, guidelines and design tools needed to construct a full-scale BTC facility and its components.

To cost-effectively build a commercial demonstration plant and manage the major risks involved, the project will be executed in two phases; a first phase to demonstrate the gasification and BTC process itself at 2.5 MWe scale with a conventional gas turbine, and a second phase to demonstrate the BTC performance at 11 MWe with the new Top Cycle gas turbine. Since the BTC technology is pressurized, the scaling of the capacity and output from phase 1 to phase 2 is done through pressure and not geometry. Doing so shortens the overall development timeline, compared to separate projects and plants, while still significantly reducing the risk of the 11 MW plant. In phase 1, the major risks in commissioning the gasification system and operating it together with a gas turbine are addressed while the Top Cycle gas turbine is in parallel being developed and tested with natural gas. In Phase 2, the Top Cycle gas turbine replaces the low pressure, conventional gas turbine, allowing power operations at full pressure, capacity and performance prior to the plant being handed over to the owner for commercial operations.

With a project start in 2023, operations in Phase 1 would start end of 2026 and last 2,5 years. Phase 2 would establish the fuel yard, a new feed line during 2029 and, lastly, install the new Top Cycle gas turbine in time for operations 2030. Further details can be found in the Appendix, while the figures below visualise the two phases of the plant.

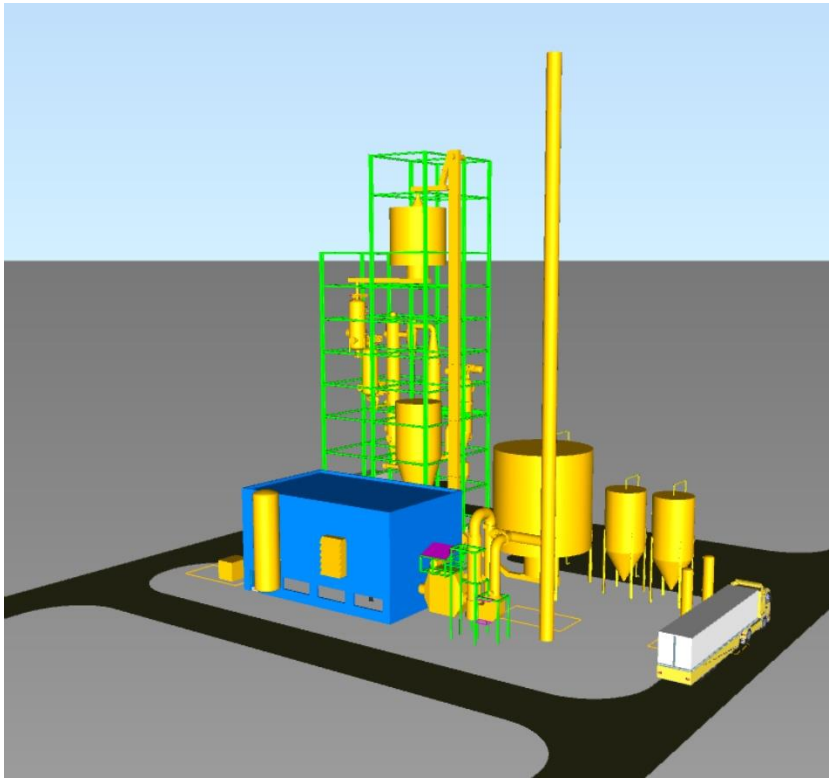

Figure 1: 3D view of the BTC Demonstration Plant, Phase 1 (2,5 MWe). The plant is operated with pellets via a single line feeding system to the gasifier.

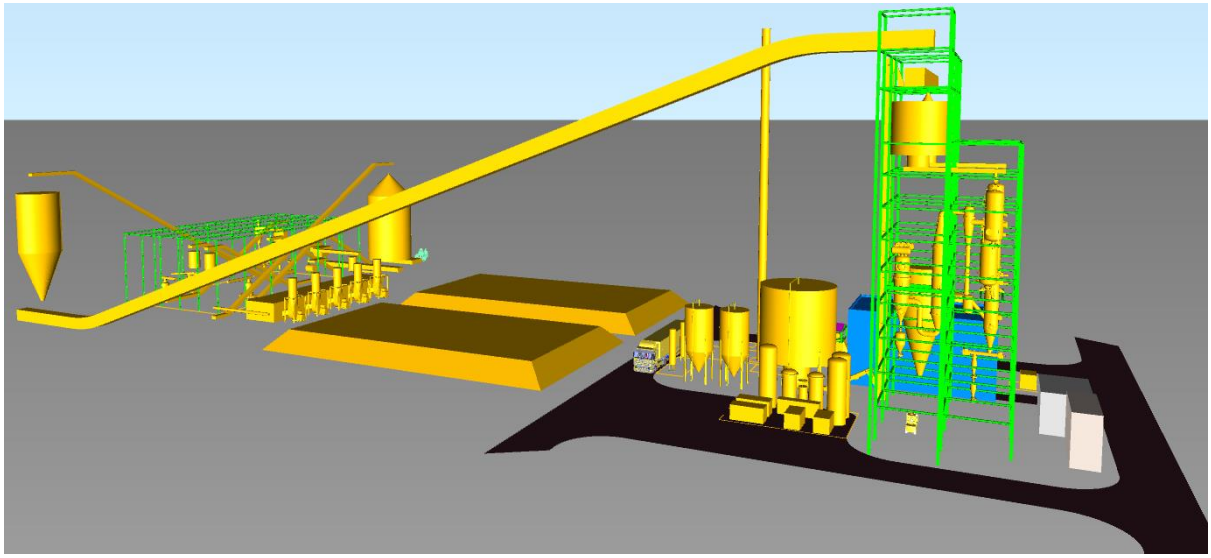

Figure 2: 3D Layout of Demonstration plant, Phase 2 (11 MWe). Plant is completed with a full fuel yard for receiving biomass, drying, and feeding to the gasification system via two feeding lines.

6 Summary and Next Steps

The project has produced the following exploitable results:

An optimised definition of the final BTC product, updated for the market developments, requirements, value and supplier capabilities has been made. The results from the market studies set the boundaries for the product specifications from a market demand perspective and identifies the plant variant size choices at 10, 40 and 100 MW for the technology development road map.

Involvement of key end-users and gas turbine supplier in pre-studies for the coming scale-up projects to full-scale demonstration unit. Thanks to this, work with the gas turbine supplier Zorya Mashproekt has now completed two concept designs for 10 and 25 MW Top Cycle gas turbine engines. Further, a pre-study is now ongoing with Drax Power Station for small-scale BECCS plant and with Växjö Energi for a large CHP plant. Several commercial contacts in addition to these have been made regarding partnership, cooperation, or possible commercial projects. The target for these contacts is to realize and commission the BTC Demonstration plant before the end of the decade.

Actionable updates have been made to the Phoenix business plan, including plans for market-entry, partnering, scale-up, financing and a proposed commercial framework for first Demo plant. This work is a crucial basis across all dimensions of work in commercialising the BTC technology and is now implemented. Externally, the results have been included in crucial documents to secure financing, i.e. in a Investment Memorandum (IM) and Prospectus. Therefore, results from the projects will be utilized in the company's funding efforts as well as lay the foundation for the commercial roll-out of the technology beginning in 2023 with the target of securing a conditional order for a first-generation demonstration plant within 24 months.

A technical and cost basis for the BTC Demonstration Plant project was developed and the associated application (sketch) was submitted to the Swedish Energy Agency call "Pilot & Demo Programme" in Q1-2023. Work will continue to develop this project to a mature level such that it can be submitted to coming calls, utilising a consortium of suppliers and utilities to ensure a feasible project. The sketch that was submitted will form the basis for a revised sketch and subsequent application to the relevant call in early 2024 or the Swedish Energy Agency and/or EU Innovation Fund.

7 Appendix

1. Market study for BTC Plants
2. Sketch for Pilot & Demo Programme
3. Investment memorandum in November 2022
4. Prospekt 2023