The Biofficiency Project Part 2: 
A Blueprint Design for the 
Next Generation of Biomass-Fired 
Cogeneration Plants

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1. Abstract

The EU-funded Biofficiency project developed a design for the next generation of biomass-fired combined heat and power plants using low quality fuels and ensuring safe and practically carbon-neutral electricity generation. In the first part of this publication (published in VGB PowerTech Journal 7 (2020)) a summary of the experiments to overcome ash-related problems in biomass-fired boilers was presented. In this second part, the new CHP concept designed in the Biofficiency project is introduced. The 300 MW$_{th}$ pulverized coal-fired boiler shown here has an overall efficiency of 92.9% and meets the ambitious emission targets of the Renewable Energy Directive RED II and the LCP-BREF. Subsequently, this article presents the technological improvements, reduced operational risks and the reduced environmental impact during power generation made possible by the project. Finally, the remaining research needs are outlined.

Throughout this article, there are several references to the project’s deliverables. All of Biofficiency’s public deliverables can be found on the European Union’s Cordis website at https://cordis.europa.eu/project/id/727616.

2. Main Text

2.1 Towards the next generation of biomass-fired CHP plants

One of the main goals of the Biofficiency projects was the design of a next-generation biomass-fired CHP plant. This design task includes multiple different viewpoints, such as the choice of location, fuel, type of power plant and so on. Within the project, a cradle-to-grave Life Cycle Assessment (LCA) was conducted for different scenarios to evaluate the impact of different design choices on the carbon, energy and water footprint, as well as the impact on human health and the ecosystem. Additionally, the socio-economic impact of the action was studied as part of a separate work package.

On the technical side, the combined experience of Biofficiency’s partners was used together with the lessons learned from the project to create a holistic design for a power plant. One example for a holistic biomass project can be found in the Äänekoski bioproduct mill by Metsä Fibre in central Finland. It is the largest wood handling unit in the northern hemisphere, consuming 6.5 million cubic meters of sustainable and fully traceable wood each year. The mill produces bio-based products like bleached chemical pulp, tall oil and turpentine, while additionally producing power and heat as a by-product. The plant covers 240% of its own energy demand and replaces fossil fuels by gasifying the produced bark and combusting the lignin inside the cooking liquor in the recovery boiler (Metsä Group, 2018), providing the grid with 1,050 GWh of green electricity each year (i.e. 2.5% of the Finnish electricity consumption).

In order to make CHP plants burning biomass similarly attractive, they need to be as efficient and as integrated as possible. This means that every plant needs to be designed specifically with its future purpose and surroundings in mind. Even the basic
question of the plant location needs to be carefully considered, keeping in mind possible fuel supply chains, storage options, availability of high voltage grid connections, financing schemes and subsidies (locally and EU-wide), proximity to a water source and/or wastewater treatment facilities. Any surrounding industry that could benefit from a synergistic relationship, for example for steam and electricity, should be considered as well. The National Technical University of Athens (NTUA) performed a study as part of the Biofficiency project in which the optimised integration of a biomass CHP plant into a heat-utilising industry and a district heating grid was investigated. The two examined industrial integration cases included an aluminium plant, as well as a reference pulp and paper mill. In the case of the aluminium plant, the possibility of covering industrial cooling demand by a biomass-fuelled tri-generation (CCHP) plant was also investigated. The results of this investigation can be found in Deliverable D7.1 of the Project as well as in a recent publication (Braimakis et al. 2020). Another study investigated the integration potential of a CHP unit into the aforementioned aluminium reference plant, considering four different raw and pre-treated fuels (Hysenj, 2018).

When it comes to the plant size, larger power plants promise higher availability, higher efficiencies and lower emissions compared to smaller plants. However, since the amount of raw biomass required for fuelling large CHP units can exceed hundreds of thousands of tons annually, the same questions regarding location and integration mentioned above arise again. A third large point is the discussion regarding fuel itself: careful consideration of the availability, sustainability, price, storability and handling is needed for a business plan. As described in part one of this report (Hansen et al., 2020), Biofficiency also investigated the influence of pre-treatment on the fuel quality, storability, combustion properties, and price. Again, the results of those investigations show that these technologies have to be selected, designed and applied on a case-to-case basis, taking into account the whole process chain.

Because the ash that accrues during the combustion process has an important influence on the economic evaluation of the process, the handling, treatment and utilisation of biomass ash has to be accounted for in a truly holistic plant design. The Biofficiency project also looked into each of these aspects, which influenced the resulting plant design towards the end of the project lifetime. The results of the ash handling issues are again found in part one of this report or in Deliverables 6.1-6.3 of the project.

2.1.1 The Biofficiency plant design

A fundamental question in boiler design is the choice of combustion system. The three main biomass power plant combustion systems are grate-firing systems, pulsed fuel (PF) systems, as well as fluidised bed systems (FB). Out of the three, PF and FB boilers currently offer the highest efficiencies and largest capacities. Since newly built PF biomass CHP plants of this size are less state of the art than FB, the Biofficiency team set out to create a state-of-the-art biomass PF CHP plant concept. A 3D rendering of the design is shown in Figure 1.

Since, as described above, the design of a power plant is highly case-specific, the Biofficiency plant was designed with a theoretical use case in mind. The plant's size (measured as fuel input) was chosen to be 300 MWth, which corresponds to roughly 18 kg of fuel consumed every second (at a lower heating value of the fuel of 16 to 17 MJ kg−1). From this fuel, around 94.4 MWth of electricity as well as 183.8 MWth of district heat is generated via a three-stage back pressure turbine, leading to an overall net fuel utilisation factor of 92.9%. Wood pellets were chosen as the plant’s fuel due to their ubiquitous availability and smaller risk of corrosion. However, the plant design enables high fuel flexibility by considering dry de-ashing with ash recirculation, thereby also allowing for higher fractions of coarse particles. Coal fly ash is added during combustion for protection of superheaters and DeNOX catalysts by capturing corrosive flue gas elements.

When it came to the choice of material, the Biofficiency plant design could rely on the results from the material and corrosion tests carried out during the project (see e.g. Deliverable 3.1). In the end, a steam temperature of 560°C was chosen as a compromise of the highest efficiencies and low risk of corrosion, also considering the limited availability of steam turbines of the chosen size with higher steam parameters. Additionally, static and dynamic simulations of the power plant were performed for final optimisations.

One important aspect was the consideration of the European Union’s Renewable Energy Directive II (RED II). In this directive, the EU set targets for new power plants in order to reach their renewable energy goals. Specifically, article 29 of the directive states that all biomass-based heat and power production sites have to reduce the greenhouse gas emissions by 70% (for installations after 1st of January, 2021) or 80% (for installations starting operation after 1st of January, 2026) compared to the EU average fossil fuel GHG emissions (183 g CO2eq/MJth for electricity, 80 g CO2eq/MJth for heat). Achieving these tar-
Biomass plays a key role in implementing EU 2020 and 2030 targets on reducing greenhouse gas (GHG) emissions and increasing the share of renewables in the energy mix. Highly efficient utilisation of biomass in CHP plants contributes to security of supply (heat and power), facilitates flexible power plant operation concerning fuel and load flexibility, enhances sustainability and improves efficiency while reducing emissions. Besides economic limitations (fuel harvesting, handling, storage, pre-treatment and transportation costs) and environmental limitations (land use changes, water consumption, deforestation), the most prominent factors preventing an increased biomass utilisation are technological risks due to corrosion and ash deposition, as well as the lack of long-term experience regarding ash-related problems.

Figure 4 gives an overview of the contributions the Biofficiency project has made along the whole supply chain of biomass CHP plants.

The project team started out by selecting and evaluating sustainable feedstock, based on availability, cost and potential. By experimental investigation of three different biomass pre-treatment technologies, optimal process conditions for the different feedstocks were developed. It was shown that biomass pre-treatment enables the utilisation of previously unusable and challenging feedstock for bioenergy purposes. Additionally, fuel handling properties are improved significantly. Techno-economic evaluations and tests carried out on larger-scale moved the market-readiness of pre-treatment technologies forwards. Evidence of this can be found in the world’s first continuous steam explosion biomass pre-treatment plant sold by Biofficiency partner Valmet in 2018, which utilises technology developed during the project.

Following a holistic approach, in which biomass combustion was studied at all scales (laboratory, pilot and full-scale) and in two different firing systems (pulverised fuel and fluidised bed), a deeper understanding of ash-related challenges could be reached, helping to enhance combustion performance and operability in biomass boilers. The design for a next generation of biomass CHP shown in Section 2.1 demonstrated that significant emission reductions can be achieved compared to coal-fired plants and smaller biomass CHP plants. The chosen plant size of approximately 300 MWth fuel input (reasonably large for biomass-fired plants) enables the operator to achieve high overall efficiency and low emissions using a trendsetting technology at cost competitive and environmentally friendly conditions.

2.2 Impacts of the Biofficiency Project

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2.2.2 Reducing the risk factors for the next development stages

The core problem for using 100% biomass in medium- to large-scale CHPs today is the technological risk of failure, shutdown or increased maintenance and repair efforts, mainly due to corrosion and ash deposition issues. Thus, current plant operators decrease steam parameters when switching from coal to biomass in order to prevent these problems. Consequently, the plant's power output and efficiency decreases. Investments in new construction and implementation of next generation plants are still withheld due to the same unsolved technological issues. During Biofficiency, technological risks associated with biomass use in CHPs were assessed and mitigation measures were identified.

Apart from the traditional risks during the operation of any power plant (fires at conveyor belts, injury of workers etc.), new technological and operational risks arise due to the new concepts introduced during the project. After consulting with experts and reviewing the literature on the likelihood and severity of each new risk, measures to reduce those risks were suggested. For the project development stage, fuel supply risk, along with the volatility of solid biofuel prices, was found to be the most critical risk factor for biomass fuelled CHP plants in Europe. The summarised results are presented in Table 2, while a detailed version of this risk assessment can be found in Deliverable 7.2.

In general, however, due to the high safety standards implemented in modern biomass plant design and operation, as well as the advanced fuel pre-treatment technologies, innovative construction materials and design principles proposed by the Biofficiency project, the overall quantitative risk assessment results are relatively low for traditional operational hazards. The standardisation of biomass fuels with the assistance of the emerging solid biofuel certification schemes will further lower the operational hazards, as well as the equipment failure risk.

Apart from technological and operational risks, social perception of bioenergy and available financial incentives are also major risk factors, as discussed in Deliverable 7.2 of the project. Stakeholders from the fields of energy and environment involved in policy recommendations and decision-making need to further stress the need for clear, concise legislation, which will aid in transparently fostering the most beneficial investments for both the environment and the EU societies, and at the same time effectively communicating the problems and mitigation strategies to the EU citizens.

### 2.2.3 Reducing the environmental impact of power generation

The combustion of biomass in a CHP plant leads to reduced emissions (GHG, NOₓ, SO₂, fine particulates) compared to the combustion of coal. The size of the biomass-fired CHP plant has a big influence on the total emissions. Medium- to large-scale units can and must achieve much lower specific emissions compared to small-scale biomass combustion systems. This is achieved by more sophisticated flue gas cleaning systems, something that is only possible due to lower specific capital expenditure in large plants. Additionally, the higher efficiency of the larger combustion plants makes a significant difference in the specific emissions. To demonstrate this, Table 3 compares the maximum emissions of the Biofficiency CHP plant design with the calculated emissions of a smaller unit with a worse efficiency. These emission values were calculated based on the assumption that the

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Technology performance before Biofficiency</th>
<th>Technology performance after Biofficiency</th>
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<tr>
<td>Net nominal electric efficiency for biomass</td>
<td>Up to 35% (for low-quality feedstocks)</td>
<td>Up to 44% (for high-quality wood pellets)</td>
</tr>
<tr>
<td>Steam characteristics</td>
<td>Up to 600°C/280 bar is reachable with an ultra-supercritical design, which is reasonable only for plant sizes larger than 300MWₑ.</td>
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Tab. 2. Emerging technological risks for Biofficiency concepts and measures taken for next development stages.

<table>
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<tr>
<th>Technological risk</th>
<th>Measures to reduce risk in Biofficiency</th>
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<tr>
<td>Fluctuating fuel quality due to environment effects or harvesting season</td>
<td>Focus on widely abundant European waste biomass species and cost-effective pretreatment technologies. Widened spectrum of feedstocks for selection according to site-specific needs (location, plant size) for supply chain optimisation. Flexible boiler technologies (e.g. FB) and fuel blends (biomassisation) are considered.</td>
</tr>
<tr>
<td>Transferability of lab-scale results to full-scale plants</td>
<td>Constant verification and comparison of investigations at three different scales (including full scale) and evaluation of transferability at each step.</td>
</tr>
<tr>
<td>Technical challenges in pre-treatment of biomass storage, milling, Missing experience for use of challenging fuels (straw, bark etc.)</td>
<td>Improve pre-treatment technologies for challenging fuels (agricultural residues, recovered feedstocks), widening biomass spectrum via improved grindability and energy density and lower fouling/sludging/corrosion propensities. Case-specific selection criteria for optimised design of appropriate pre-treatment method.</td>
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Costly disposal of ash due to lack of possible utilisation routes because of chemical and physical properties of some ashes

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<tr>
<th>Likelihood: medium</th>
<th>Severity: medium</th>
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Material / equipment failure due to corrosion caused by biomass composition, unpredictable increase of costs

| Likelihood: low | Severity: high |

Increased security and planning reliability through guidelines based on real-scale expertise, as well as advanced materials selection with high resistance against corrosive environment. Enhanced plant availability due to improved equipment design. In-depth understanding of corrosion and deposition mechanisms for a variety of biogenic fuels.

Low CHP plant availability due to lack of real-time furnace diagnostics (FB boilers)

| Likelihood: low | Severity: high |

Development and optimisation of diagnostic tools for use in biomass-fired CFB boiler-equipped CHP plants (sensor technology, evaluation criteria) leading to higher availability and lower operational costs.

High emissions from biomass combustion (CO₂, NOₓ, SO₂, particulate matter)

| Likelihood: low | Severity: high |

Investigation of primary measures through fuel staging and additive utilisation. Reduction of NOₓ and NO under (circulating) FB conditions simultaneously. Implementation of an advanced flue gas cleaning system. Reduction of particulate matter through pre-treatment and improved equipment design, removal of alkali metals.

Too conservative plant design

| Likelihood: low | Severity: high |

New design of next generation power plant with focus on the fuel and its composition, such as ash and chlorine content. Improved plant economics through slim design (especially regarding the flue gas cleaning section).

Seasonal shortage of supply

| Likelihood: high | Severity: high |

Investigation of a number of fuel pretreatment technologies to broaden the portfolio of suitable feedstocks towards improved operation, leading to better storability. Identification of advanced corrosion-resistant materials to facilitate combustion of more challenging feedstocks.

Tab. 3. Comparison of specific emissions at large and small plants.

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<th>Large unit (299 MWₑ, fuel input, 95 MWₑ, 184 MWₑ, 31.5 %, 92.9 %)</th>
<th>Small unit (20 MWₑ, fuel input, 4.1 MWₑ, 20.6 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOₓ</td>
<td>50 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
<td>50 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
</tr>
<tr>
<td>SO₂</td>
<td>69.2 g/MWh (total)</td>
<td>75.6 g/MWh (total)</td>
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<tr>
<td>Dust</td>
<td>10 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
<td>10 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
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<tr>
<td>13.8 g/MWh (total)</td>
<td>15.1 g/MWh (total)</td>
<td>15.1 g/MWh (total)</td>
</tr>
<tr>
<td>2 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
<td>2 mg/m³ (N.dry) Ø6 % O₂ (yearly average)</td>
<td></td>
</tr>
<tr>
<td>2.8 g/MWh (total)</td>
<td>3.0 g/MWh (total)</td>
<td>3.0 g/MWh (total)</td>
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3. Conclusions

The Biofficiency project has contributed tremendously to the state-of-the-art in biomass combustion for generation of heat and power. The first part of this article already highlighted the advancements in the state-of-the-art in pre-treatment, process operation, material selection as well as numerous ash-related topics like ash formation, corrosion mitigation and biomass ash utilisation. In this second part of the article, it was highlighted how the results and experiences gained during the project were used to create a holistic, next-generation power plant design. Biofficiency covered each aspect of the challenges that occur during this shift towards highly efficient biomass-fired CHP plants.

Starting from a thorough risk assessment of the operational, technological and socio-economic risks of such a new plant, a life cycle assessment combined with investigations towards the integration into other existing industry was carried out. Using static and dynamic simulations and keeping in mind the legislative restrictions on emission levels, a 300 MWₑ wood-fired PF power plant was designed. It manages to reach a 92.9 % net fuel utilisation factor and meets the emission targets of the RED II and the LCP-BREF by utilising an advanced flue gas cleaning system and dry deashing with ash recirculation.

4. Outlook

While a huge impact could already be achieved within the project lifetime, the consortium anticipates a number of further activities.

Industrial partners plan on further dissemination of the results, offering services for biomass combustion projects. Especially, the commercialisation of the designed highly efficient od high efficiency biomass fired power plant will be in focus. Dissemination of results to the scientific community will also continue by publication of peer-reviewed papers with Open Access.

Moreover, the knowledge gained in Biofficiency will be applied to other currently running projects, like the conversion of the Rotterdam power station and others from coal to wood.

Some additional research needs were identified during the final phase of the project.

- Large-scale testing of challenging biomass (pre-treated and raw)
- Identification of suitable combination of pre-treatment and adjustment of combustion/boiler
- Investigation of fine particle formation and deposit build up by use of other additional additives
- Further improving modelling of deposit formation
- Predicting the behaviour of fuels and fuel mixes with an even higher confidence
- Identification of temperature limits for different materials and different fuel mixtures
- Demonstration on demo/industrial scale the ash application possibilities
- Influence of biomass properties on milling and combustion efficiency
- Comparing sustainable energy from biomass with biodiesel from palm oil, from rapeseed oil, etc. by in depth LCA

By tackling these challenges and utilising the full potential of biomass-based energy, a significant part of the goal of a sustainable and carbon-neutral future can be reached.
5. Acknowledgement

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6. Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>PF</td>
<td>Pulverised Fuel</td>
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<tr>
<td>FB</td>
<td>Fluidised Bed</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>LCP-BREF</td>
<td>Large Combustion Plants – Best Available Techniques Reference</td>
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<td>RED II</td>
<td>Renewable Energy Directive II</td>
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<td>GHG</td>
<td>Greenhouse Gases</td>
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<td>PPE</td>
<td>Personal Protective Equipment</td>
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<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>EU D</td>
<td>European Union Deliverable</td>
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7. References


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