Final report

1.1 Project details

Project title	Torrefaction Development and Demo Plant
Project identification (program abbrev. and file)	EUDP – 2010, J. Nr. 64010-0461
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Andritz Feed & Biofuel A/S, Glentevej 5-7, 6705 Esbjerg
Project partners	Danish Technology Institute DONG Energy Drax Power Ltd (later withdrew)
CVR (central business register)	438 54 410
Date for submission	06-03 2017

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GUIDELINES FOR FINAL REPORT

1.2 Short description of project objective and results

The project objective was to demonstrate technology for a pressurized torrefaction reactor capable of producing up to 500,000 t/y of torrefied material from wood (~10 times "normal" torrefaction reactor technology) at full scale, in support of the then growing market for using biofuels in coal fired power plants to limit green-house gas emissions. A 24 t/d plant complete from wood intake to finished pellets was built and operated for more than 12 months. After initial testing and some modifications, it was successful in proving the torrefaction technology, whereas pelleting proved difficult due to high power consumption and excessive equipment wear, compared to pellet production from untreated wood. Much was learned about optimizing and balancing the reactor process relative to different species of wood, and handling of the reactor gases and condensation products formed. 200 tons of torrefied pellets were produced and successfully co-fired with coal in DONG's power plant in Studstrup. The experiences generated at the test plant showed that the any torrefaction process is too costly in the present energy market, greatly reducing the interest in commercialization of the concept for production of power plant fuels.

Formålet med projektet var at udvikle torrefaction-teknologi for træ til kraftværksbrændsel som erstatning for kul og dermed i support af reduktion af drivhusgasser.
Et yderligere formål var at demonstrere fordelene ved tryksat reaktor teknologi for fremtidige fuldskala produktionsanlæg med kapacitet op til 500.000 tons per år, hvilket er 10 gange højere kapacitet end muligt med kendt, ikke tryksat reaktor teknologi.
Der blev under projektet bygget et komplet procesanlæg fra indtag af træflis til færdigt torrefieret og pilleteret kraftværksbrændsel med en kapacitet på 24 tons per døgn brændselspiller.
Anlægget var i drift i 12 mdr. Driften af anlægget beviste funktionaliteten af den tryksatte reaktor og mange resultater og erfaringer blev genereret vedrørende procesgasser og kondensater fra torrefaction processen.
Det blev under driften af anlægget samtidig klart at pelletering af torrefieret træ er procesteknisk vanskeligt, meget energikrævende og samtidig meget slidende sammenlignet med traditionel pilletering af ubehandlet træ.
200 tons piller af torrefieret træ blev produceret og prøveforbrændt med godt resultat på DONGs kraftværk i Studstrup.
Erfaringerne fra driften af anlægget viste samtidig at processen er for dyr i nuværende energimarked, hvorfor der ikke på kort sigt er muligheder for storskala udnyttelse af teknologien til produktion af kraftværksbrændsler.

1.3 Executive summary

A 24 t/d pressurized torrefaction plant complete from wood intake to finished pellets was built and operated for more than 12 months. After initial testing and some modifications, it was successful in proving the torrefaction technology, whereas pelleting proved difficult due to high power consumption and excessive equipment wear, compared to pellet production from untreated wood. Much was learned about handling of the reactor gases and condensation products formed. 200 tons of torrefied pellets were produced and successfully co-fired with coal in DONG's power plant in Studstrup. The experiences showed that the process is too costly in the present energy market, decreasing interest in commercialization of the concept for production of power plant fuels. If future economic or regulatory conditions change in favour of alternative solids fuel sources, the data collected and operating and equipment design experience will be very valuable for designing full scale (up to 500,000 t/a) wood torrefaction plants.

1.4 Project objectives

1.4.1 Objective of the Project

Torrefaction technologies presented at the time of the project inception in 2011 were only capable of producing approximately 50,000 tons per year of torrefied material, due to design constraints which do not allow for larger equipment. The multiple reactors required for larger plants would be very expensive to purchase, maintain and operate. The proposed torrefaction technology in this project relied on equipment designs from the pulp and paper industry, where some of these designs are operating at approximately 2,800,000 tons per year.

Further, the proposed technology relies on nitrogen circulating through the wood chips at pressures between 4 and 10 bar (g). A notable feature of this process is the ability to use nitrogen rich cooling gas from the bottom of the reactor (which would otherwise be purged from the system) as part of the gas for the heating zone of the reactor. By using this nitrogen rich gas a balance can be established in the both the cooling loop and the heating loop with minimal addition of make-up nitrogen.

Andritz believes that the production rates achievable by this technology, along with the above mentioned benefits of operating the system with recirculating nitrogen flows offer the clearest and most economical path for large scale torrefaction technology to the market place. All of the equipment in the proposed Andritz torrefaction system is in its fundamental designs based on proven technology currently in use in the pulp and paper industry, adapted to become functional at the different process parameters of the torrefaction process.

Benefits of Torrefaction for the customer:

- Increased energy density compared to wood or wood pellets
- Higher degree of co-firing with coal (up to 70%, currently ~15 -30 % for wood pellets)
- Lower transportation costs
- Green alternative, lower net CO2 emissions
- Renewable energy source, addresses targets set for phasing out fossil fuels
- Lower NOx, SOx and ash emissions than coal

- Less slag compared to un-Torrefied biomass
- Easily ground / pulverized -> lower power consumption requirements at the power plant
- Physical properties closer to coal when compared to wood pellets -> little or no additional investment needed at the power plant
- Improved boiler efficiency
- Offers cleaner burning fuel with lower volumes of flue gases

Each ton of Torrefied wood burned in a coal fired facility reduces the fossil fuel CO2 output by up to 2.4 tons.

The project consortium covers large, well established companies with a proven track record in the entire value chain from production of torrified biomass, production of pellets and large-scale power plants. The selection of partners combined with the unique technology and up-scaled size of plant is the the main incentive for developing this project.

For the project team, the above objectives and goals translated into the need for:

- Conceptual design
- Systems and Equipment design
- Layout, building and plant design.
- Procurement
- HAZOP and Safety
- Automation
- Training
- Commissioning
- Start-Up
- Testing

Wood to be tested in the Demo Phase (Andritz Runs) per the EUDP agreement was initially scheduled to be:

- Scandinavian Pine,
- Southern Yellow Pine**
- Eucalyptus,
- Aspen,
- Birch
- Mixed Hardwood (Beech, Maple, Oak etc.)

** Subsequently, it was determined that North American softwood cannot be imported to Denmark without certification of heat treatment, which would make using this wood source impractical.

For the above six types of wood, the following targets were set:

- Torrefaction to at least 26% dry biomass loss
- Minimum pellet quality at this torrefaction level
- Bulk density at least 630 kg/m3 for Ø8 mm pellets
- Maximum 5% final moisture content.
- Power consumption for pelleting < 70 kWh/ton product

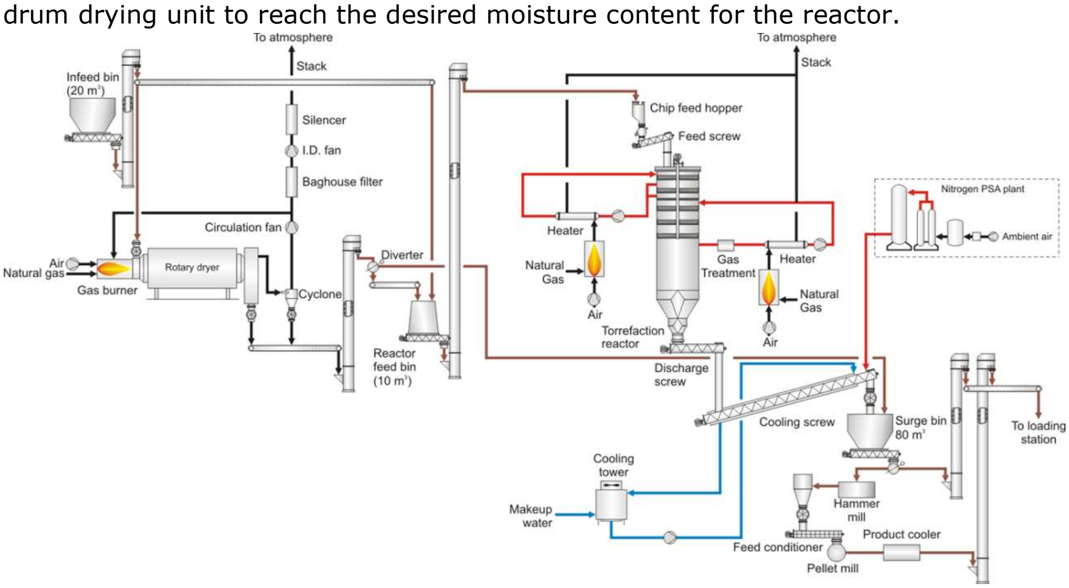
We were to test the process and grade of torrefaction of the selected biomasses should be monitored through the following analyses:

- Yield determination based on bulk density testing, composition of input and torrefied materials, and mass balance.
- Carbohydrate, lignin and extractives composition of input and torrefied materials.
- Size distribution of input and torrefied materials.
- Heating value (GCV) of input and torrefied materials.
- Moisture content of input and torrefied materials.
- Heating value (GCV) of vent gas from reactor system.
- Organic content in vent gas from reactor system.
- Additionally, we decided to test volatiles of the feed material and torrefied material.

1.5 Project results and dissemination of results

1.5.1 Description of the Installation

The pilot plant incorporates biomass receiving, drying, torrefaction, and pelletizing in an integrated system. The torrefaction process blends ECN and ANDRITZ technologies and has been patented. Fresh wood chips are first dried in an ANDRITZ rotary drum drying unit to reach the desired moisture content for the reactor.

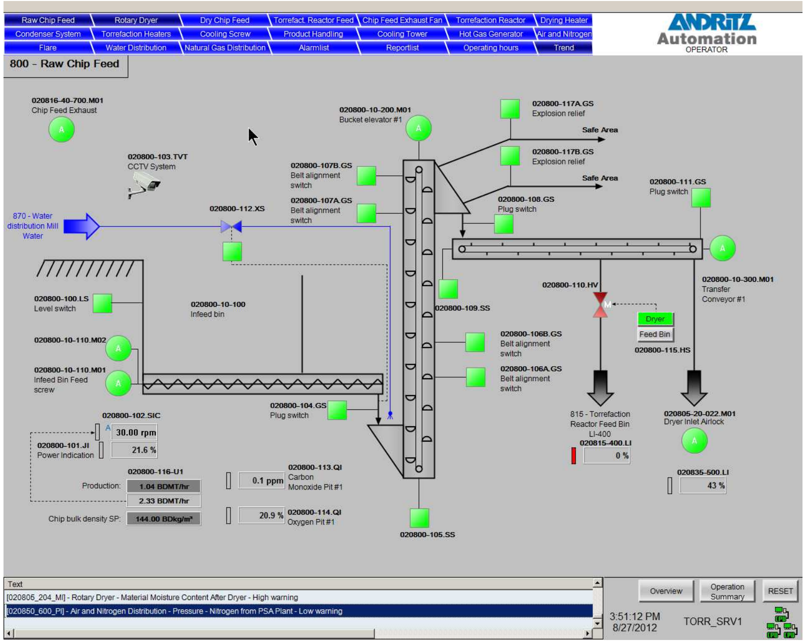


The heart of the process is a vertical pressurized reactor. Inside the reactor, there are trays (beds) stacked vertically. Dried wood chips enter the reactor at the top, "roast" in the hot gases passing through the biomass and perforated trays which rotate to ensure even distribution, then drop to the tray below for another stage of torrefaction. The torrefied material is discharged at the bottom of the reactor vessel. From the reactor, the torrefied material passes through a cooling screw to a storage silo. For the densification process, the material passes through an ANDRITZ hammer mill for crushing to uniform size before entering the ANDRITZ pellet press, resulting in an energy-dense torrefied pellet that can be stored and shipped to customers.

The process design was analyzed according to ATEX procedures dealing with potentially explosive atmospheres. Torrefied dust is potentially explosive when mixed with air, so considerable engineering effort and investment was used to reduce the risk. This included extensive testing of eucalyptus and pine dust. The pilot plant was equipped with safety systems to mitigate the risk of fire and explosions.

Examples of DCS screen shots and pictures of the Demo Plant equipment are shown below.

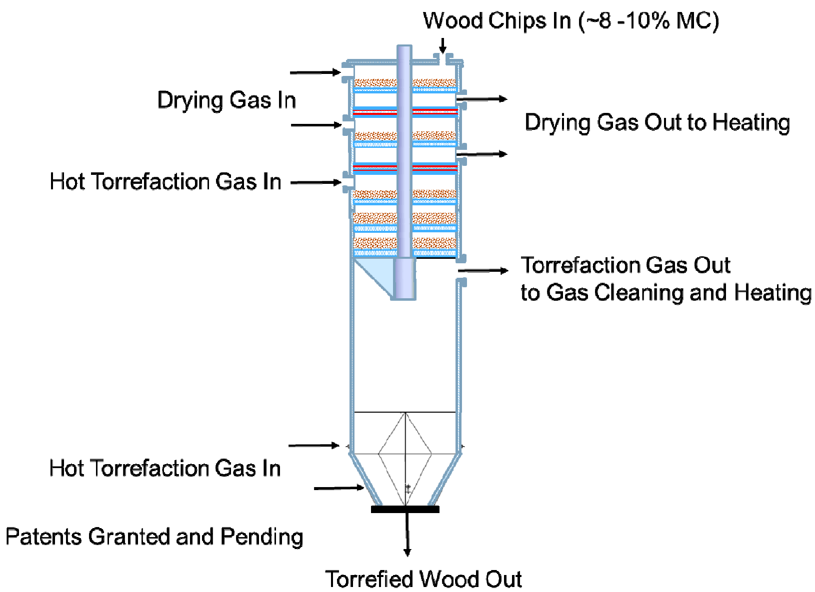
1.5.1.1 Raw Material Receiving



1.5.1.2 Biomass Dryer

The Rotary Dryer in the test plant

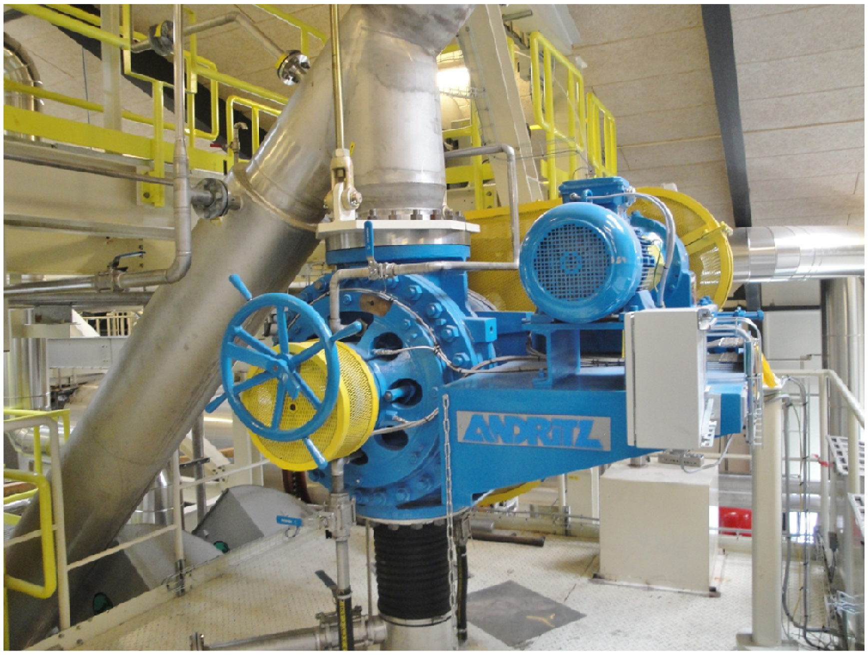
1.5.1.3 Torrefaction Reactor



Torrefaction Reactor Process Area

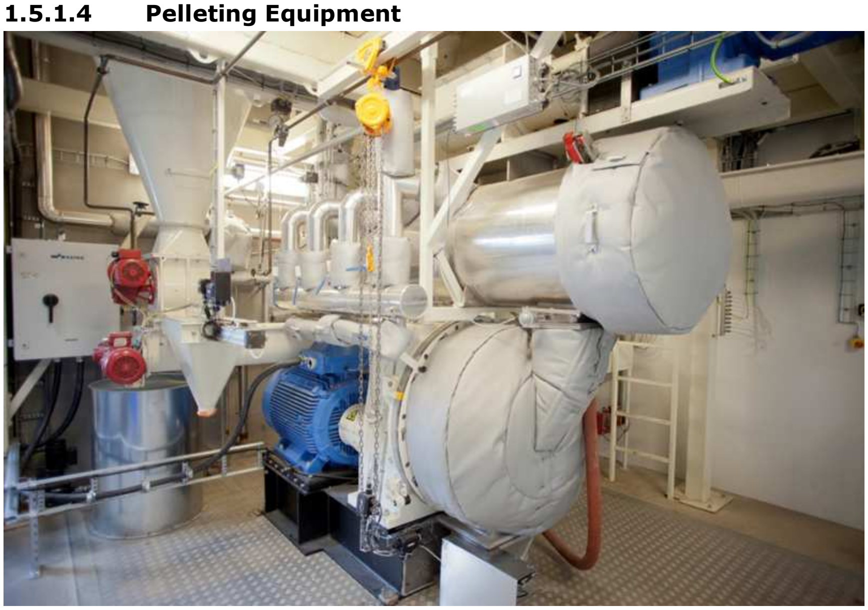
Patents granted and Pending

The 1 tph torrefaction reactor in the test plant



Upper Part of Torrefied Material Cooling Screw and Discharge Rotary Valve

1.5.1.4 Pelleting Equipment



Material pre-conditioning and pellet press installation in the test plant.

1.5.1.5 Big Bag Loading Station

Torrefied Wood Chips

Pellets

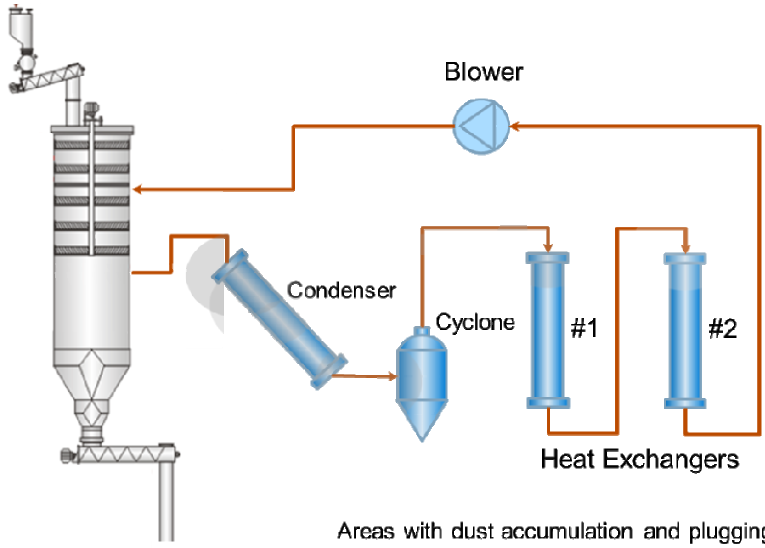
1.5.2 Operation Tests and Trial Runs

1.5.2.1 Redistribution of the reaction zones

The torrefaction reaction is a strongly exothermal reaction, leading to difficulties to control the temperature, especially in the bottom bed of the reactor, which in turn led to overtreatment of the wood chips and fusing of the bed. As the operation showed good torrefaction results when operating without a level in the lower part of the reactor, it was decided to abandon attempts to use the lower part of the reactor for retention time. This also simplifies the design of a commercial size reactor.

1.5.2.2 Solutions avoiding sawdust buildup

Sawdust coats the circulation lines and equipment, causing operating disturbances. The installation of a chip screening system resolved this issue. The fines removed by the screens would be used for heat generation for the biomass dryer in a commercial plant.



Areas with dust accumulation and plugging

 Photo of the inlet tube sheet on the condenser during later part of 2012	 Top of #1 Heater in the Torrefaction Loop. Significant deposits caused blockage and required cleaning after 4 to 7 days of operation.


Vibratory Screen Installation for chips cleaning prior to torrefaction.

Accept Chips to Torrefaction

Rejects from the Vibratory Screen

1.5.2.3 Equipment design issues realized and modified for more reliable construction

Several equipment failures led to redesign and modifications.

1.5.2.4 Fire and Dust Explosion Experience and Prevention

The pellet press operation incurred several small fires and one severe dust explosion in the pellet cooler. The explosion event activated the fire suppression system and activated the alarm to the fire department. No personell injuries occurred. The root cause was determined to be insufficient cooling air flow, allowing dust to be ignited by the hot pellets dropping from the pellet press.

While the protection system worked as designed, the design and operating team identifeid and implemented multiple changes to instrumentation and procedures, after which no further incidents occured.

1.5.2.5 Leakage of torrefaction reaction byproduct gases from equipment seals.

During the early weeks of operation, elevated levels of carbon monoxide were at times detected in the building. Modifications were made to the relevant equipment including installing and improving nitrogen purging of equipment seals in order to reduce the gas leakage. Nitrogen pressure was subsequently controlled to always exceed the reactor pressure.

1.5.2.6 Tar Deposits

The volatized reaction products from the torrefaction process may condense if exposed to lower temperatures, and form a tar-like substance, which will not re-vaporize when exposed again to higher temperatures. Physical or chemical cleaning will be required to remove it. Preparations to control tar removal were built into the system as designed, based on experiences from the ECN pilot plant in The Netherlands. The tar deposits were not found where we expected them , but rather in other areas. We also found that we could control the tar deposits by having a very strict control of the temperature and gas flow profile in the reactor.

1.5.2.7 Pelleting Issues and Results

Once the torrefaction reactor reliability had reached a point where the rest of the plant could be tested for longer operating periods, the focus was on testing and optimizing the pelleting operation.

We found that pelleting spruce material which had been torrefied to higher degrees of torrefaction was very challenging. It was also during this period we encountered the previously discussed issues with fires in the cooling system after the pellet press.

Despite the issues with pelleting process, we were producing pellets which were near meeting the required quality parameters, when operating with fully torrefied material.

- There is some, but not full hydrophobicity of pellets made from torrefied wood
- Durability of the pellets is in the right range.
- Dust in pellets is above target.
- The grindability has been significantly improved.
- Pelleting power consumption on a kW/Ton basis is often about double the design target. 130 kWh/ ton vs. 70 kWh/ton

The torrefied wood particles seem to subject the die channels to very high friction, resulting in the generation of considerable heat. Often the pellets leaving are at temperatures greater than 200 oC, resulting in fires in the pellet cooler.

The natural binding properties of the wood are substantially reduced by the evaporation of hemicellulose and partly the lignin as result from the torrefaction process.

Reduction of the compression ratio of the die reduces (as expected) the friction and power consumption, and consequentially also the density and durability of the pellets

Small variations in the wood or the degree of torrefaction cause large variations in the abovementioned friction and related power consumption.

This makes the torrefaction pelleting process much more sensitive and more difficult to balance than conventional fresh biomass pelleting.

The high friction of the dust and the subsequent high power consumption results in rapid wear of the pellet dies and too frequent failure of the bearings in the pellet rollers.

Application of small amounts (0.2 - 0.8 %) pine oil reduces, but does not solve the high power consumption problem.

The work identified multiple modifications needed for the pelleting system and pointed to the need for a design of a more robust pellet press compared to the designs used for conventional biomass pelleting

- to be able to handle the in general higher specific power loadings and the further peak loads occurring as result from small variations in the torrefaction process .
- To allow for dynamic control of the die temperature (Cooling and Heating at times).
- Have more wear resistant dies.

Due to the vaning interest for torrefied materials in the marketplace, it was decided to not proceed with this development work. Even with a more robust press, equipment wear would be a considerable issue in a commercial plant.

The table below summarizes the results from production runs on different wood species. Due to supply issues, all wood species specified in the EUDP application could not be tested. Other wood species were used instead. While good quality pellets could be produced, the power consumption and equipment wear were unreasonably high. Using 6 mm diameter pellet dies improved the situation over 8 mm dies, but would still not economically permit commercial pellet production.

	Targets						
	Torrefaction Mass Yield %	Pellet Bulk Density kg/m^3	Final Moisture Content %	Pellet Mill Power Consumption kWh/ton	Durability %	Pellet Size mm	HHV MJ/kgBD
All Wood Types	<76	>630	<5%	<70	N/A		
	Achieved Results						
Wood Types							
Scandinavian Spruce	~78	650	<5%	120	95.5	6	22.2
Cedar	~74	660	<5%	175	95	8	22.7
Eucalyptus	~67	700	<5%	135	97	8	21.7
Beech	~63	650	<5%	100	98	6	22.0
Aspen (Poplar)	N/A	700	<5%	70	98.5	6	N/A
Scandinavian Pine	No results. Spruce was used instead.						
Birch	No results. Beech was used instead.						
Mixed Hardwoods	No results. Beech was used instead.						
Southern Yellow Pine	No results. Could not be imported to Denmark						

Additional results from tests which were to be conducted:

- Carbohydrate, lignin and extractives composition of input and torrefied materials.

	Targets					
	Arabinan %	Galactan %	Glucan %	Xylan %	Mannan %	Lignin %
	Achieved Results					
Torrefied Wood						
Scandinavian Spruce	0	0.4	48.5	1.1	2.8	45.7
Cedar	0.2	0.3	42	1.7	3	50.9
Eucalyptus	0.1	0.3	51.5	1.7	0.6	43.5
Beech	0.1	0.2	48.6	4.1	0.5	44.3
Aspen (Poplar)	No results. Project was terminated before testing was completed.					
Scandinavian Pine	No results. Spruce was used instead.					
Birch	No results. Beech was used instead.					
Mixed Hardwoods	No results. Beech was used instead.					
Southern Yellow Pine	No results. Could not be imported to Denmark					

- Size distribution of input and torrefied materials.

This was done mainly to check the amount of dust.

- Heating value (GCV) of input and torrefied materials.

The HHV values for the torrefied wood pellets shown above are ~10% higher than for the wood input, both measured on a dry material basis.

- Moisture content of input and torrefied materials.

The moisture content of the wood input varied between 40% for Eucalyptus and 60% for Scandinavian Spruce. The torrefied material always had moisture contents less than 3%. In the pellet operation, the material is conditioned using steam and water, but the final product mositure content is less than 5%

- Heating value (GCV) of vent gas from reactor system.

This was not tested, mainly due to safety concerns surrounding the sampling of the gases.

- Organic content in vent gas from reactor system.

This was not tested, mainly due to safety concerns surrounding the sampling of the gases.

- Additionally, we decided to test volatiles of the feed material and torrefied material.

This was done a routine basis, and was used to determine the mass yield.

1.5.3 Contract production runs

During the period of February through June, 2013, the plant operating team primarily focused on learning to improve the operation of the pelleting process, in additon to running several third party production runs.

The EU ”Sector” project required torrefied pellets for testing for which the Dutch company Topell had originally been contracted to provide the material, but due to their extended outage/rebuild, they sub-contracted the material supply to Andritz. We provided material as follows.

Company/organization	Quantity
Company A, Austria	3 kg
Company B, Austria	0.75 tons
Company C, Germany	1.1 tons
Company D, Austria	1.5 tons
Coimapny E, Germany	4 tons
Company F, Sweden	2 x 2 tons = 4 tons
Company G, UK	2 x 5 tons = 10tons

1.5.4 Co-Firing at Dong Energy

As part of the EUDP project, Dong Energy committed to make a test burn with the torrefied material from the Sdr. Stenderup Torrefaction Demonstration Plant. During the August and September 2013 time period, 200 tons of torrefied pellets were produced using Danish spruce as the raw material.

On Friday 21 March, 2014, the combustion test with torrefied pellets was conducted at Dong Energy power plant, Studstrupværket.

Due to a poor condition of the containers supplied by Dong, rain had entered almost all of the containers, wetting 5-10% of the pellets. It was decided to run all pellets; wet and dry. There were no handling or combustion operational problems at all, which is very positive when considering outside storage in a commercial plant.

The grinded pellets quality was considered to be satisfactory.

The boiler had 24 burners, where 6 of them were dedicated to the torrefied pellets and 18 for coal

The share of biomass run in the furnace was 31,8%.

The flame at the burners was recorded and evaluated to be very good.

The operators in the control room said it was a very easy fuel to run with and it was clear to them that the properties of the pellets were similar to coal

Overall Dong was very satisfied with the performance of the pellets.

The pictures show the un-loading of pellets from a container and the pellet silos used to feed the material to the grinder.

1.6 Utilization of project results

The development work was very successful in showing that torrefaction of wood in a pressurized reactor can be performed as intended. Unfortunately, the pellet operation proved to be more difficult than expected. While in could be possible to develop the pelletizing properties, we concluded that this could only be done using additives, which would further increase the cost of making the pellets.

It may be possible to use torrefaction as a pre-treatment for other conversion technologies which do not require pellets, but that was not the objective of building the demo plant. So unless a change in general fuel cost or government regulations, we do not presently view torrefaction of biomass for fuel purposes (Andritz solution or anybody else's) as a viable commercial industry.

If a shift in pricing or policies changes this view, Andritz has collected the technical information needed to be able to design full-scale plants.

The work before and during the operation of the demo plant resulted in several granted patents.

Selected experiences and results from the project have been presented at public conferences. There has been no other transfer of the results to other research institutions.

1.7 Project conclusion and perspective

The experiences and conclusions generated from the project are that any torrefaction process is too costly in the present energy market, the additional costs of generating torrefied pellets compared to conventional biomass pellets are substantially higher than the perceived added value / additional price obtainable in the energy market. This leads to a much reduced interest in commercialization of the concept for production of power plant fuels, unless there is drastic shift in fuel costs or government regulation.
Despite several attempts to generate new interest for the technology, and conduct further torrefaction pelleting and related combustion trials, the interest from the potential off-takers has diminished.
We have found no energy companies or other potential off takers with willingness to pay a price covering the costs to generate further amounts of fuels for test combustion.
We have therefore been searching for other industries for which the torrefaction process and related technologies of the test-plant could be of potential interest, but so far without results.
Therefore the plant has been idle since the conclusion of the combustion tests with DONG in late 2013.
As we see no short or mid-term use for the plant, plans for demolition of the test plant in 1 H 2017 is in development.

06. – 03. 2017. Andritz Feed & Biofuel A/S Finn Normann Jensen