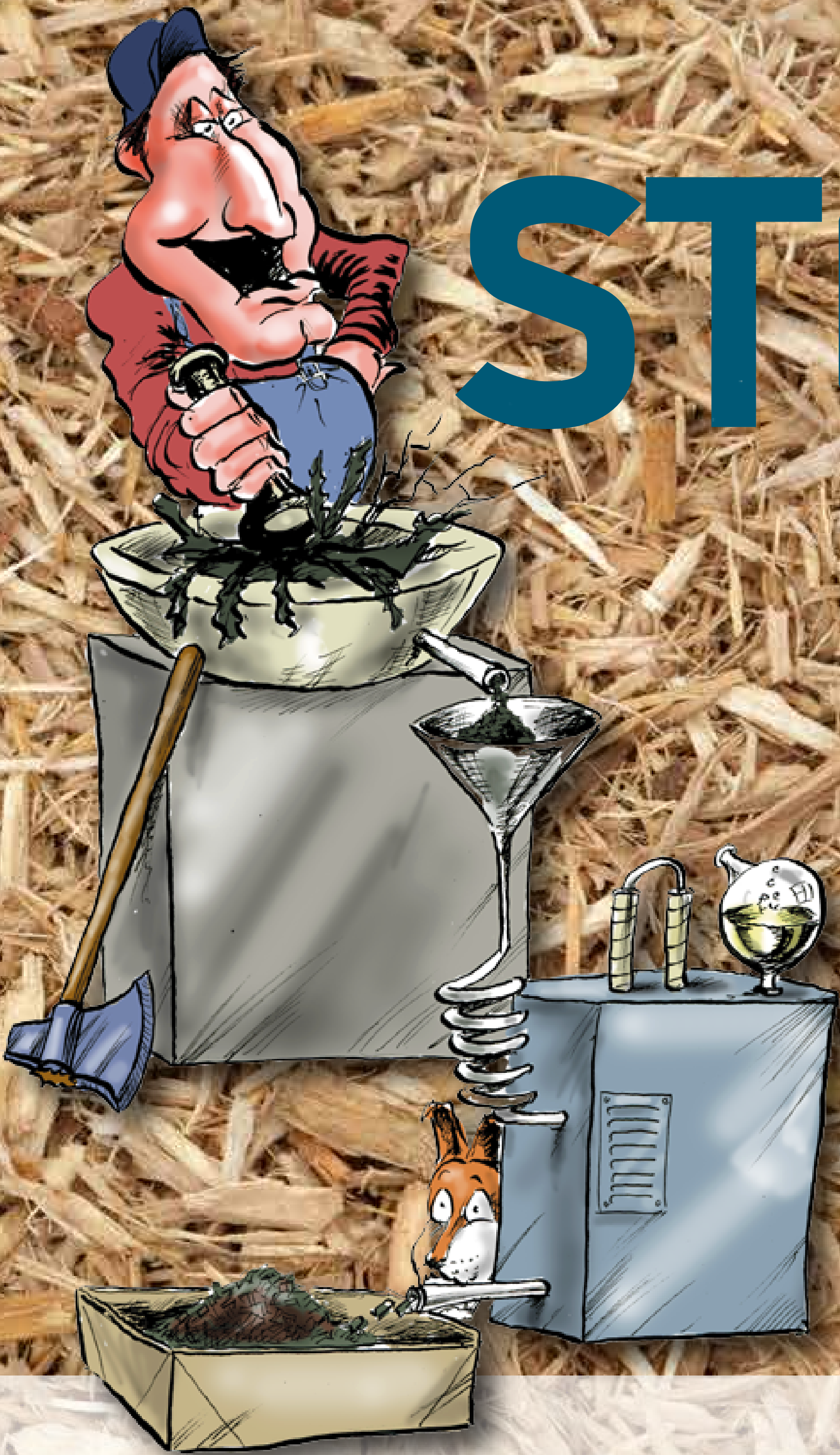
STOP



STable OPerating conditions for biomass combustion plants

SINTEF

STable OPerating conditions for biomass combustion plants

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Background

This handbook has been prepared by SINTEF Energy Research with the purpose to provide both partners of the STOP project and others with a simple and easy to read guide on how to obtain stable combustion, or gasification, conditions in biomass energy conversion plants.

The information in this handbook has mainly been obtained by studies performed throughout a 4 year project period in the competence building project entitled: "STOP – STable OPerating conditions for biomass combustion plants".

The project has been financed by the Research Council of Norway and industry and has operated under the umbrella of the CenBio (Bioenergy Innovation Centre) FME (Center for Environment Friendly Energy Research).

The main objective of the project was as follows:
Development of new strategies for improved operating conditions control in biomass and biomass residues combustion plants through

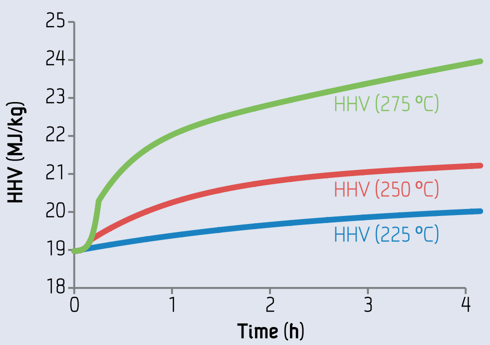
- The utilization of more homogenous fuel with minimized season variation
- Optimized fuel in terms of pollutant emissions
- Improved fuel quality through torrefaction

Most of the research concentrated on the topic "torrefaction" which is a thermal pretreatment method aimed at improving the fuel quality of biomass in order to attain "predictable" conditions during energy conversion. During torrefaction, biomass is heated to a temperature range of 200 – 300 ^{0}C and kept at this final temperature for a certain time (typically 30 – 60 minutes). The resulting product is still very different from charcoal and has a brown color which becomes darker as the torrefaction temperature is increased.

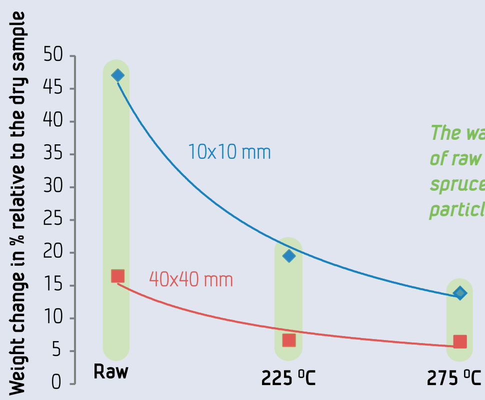
Torrefaction is a low-temperature process similar to that used for roasting coffee beans.

What are the advantages of torrefaction?

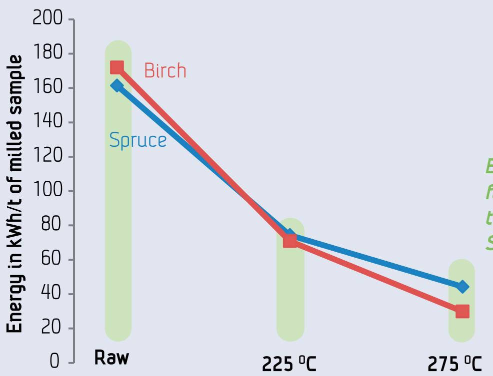
1. Right after torrefaction, the energy content per unit volume decreases, but increases per unit mass. This means that the **energy density will increase** in comparison to the raw fuel, if the torrefied material is ground and compressed afterwards.
2. **Hydrophobic nature**, meaning that the final product will have low moisture content and will not absorb significant amounts of water while stored. As a consequence of being water repellent, torrefied biomass will not deteriorate in quality through biological degradation, which is the case for virgin biomass.
3. **Enhanced grindability** due to the loss of its fibrous structure and becoming brittle which results in much less energy consumption during milling.
4. Better **particle size distribution, smaller particles** which reduce residence time requirements for complete conversion and more **spherical particles** which gives enhanced aerodynamic properties.
5. High **particle porosity** which results in greater reactivity due to a larger surface area available for reaction during combustion and gasification



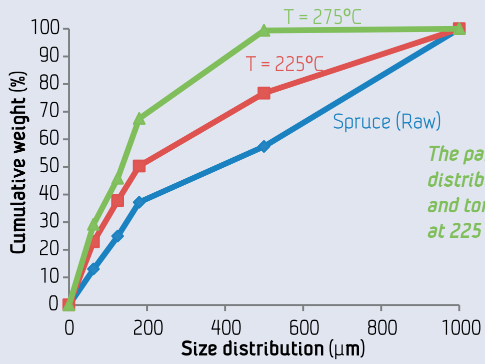
The modeled higher heating value of spruce at different temperatures as a function of residence time.



The water uptake of raw and torrefied spruce for two particle sizes.



Energy requirements for grinding of raw and torrefied fuels; for both Spruce and Birch.



The particle size distribution of spruce and torrefied spruce at 225 and 275 °C

Wet torrefaction

Wet torrefaction may be defined as treatment of biomass in a hydrothermal medium, or hot compressed water, at temperatures within 180-260^{o}C.

It is more likely to be beneficial for wet biomass feedstocks such as sewage sludge and wet agricultural wastes, although drier biomass feedstocks can also be used.

The aim of this pretreatment is similar to "dry" torrefaction, i.e. improving the fuel properties. Apart from the solid fuel product, some water, CO_2, small amounts of CO, H_2, some hydrocarbons, and dissolved organic and inorganic compounds are released from biomass during wet torrefaction. The dissolved organics make up approximately 10 % of the mass of the feedstock and include compounds such as acetic acid, formic acid, lactic acid, glycolic acid, levulinic acid, phenol, furfural, 5-hydroxymethylfurfural (HMF), and sugars.

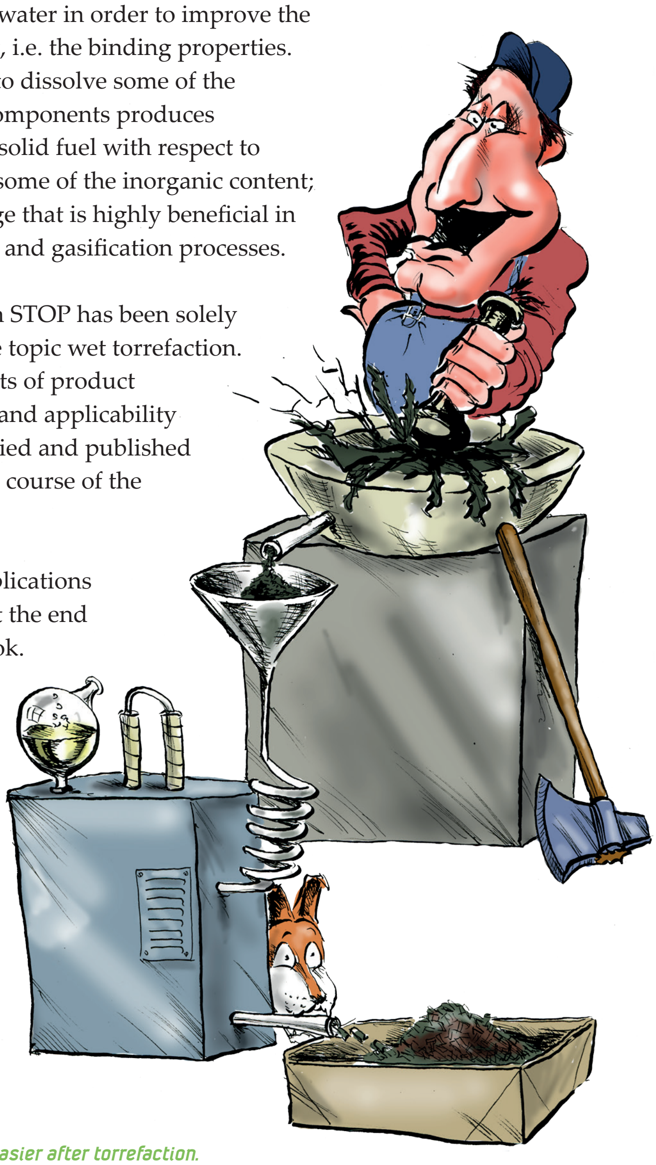
The potential use of these water soluble organics for the production of valuable products may contribute to further improve the cost-efficiency of wet torrefaction.

Wet torrefaction has some advantages compared to dry torrefaction. Among these are:

- The elimination of the pre-drying step as pretreatment takes place in a hydrothermal medium.
- Easier pelletization because the wet torrefied biomass does not require the addition of water in order to improve the pelletability, i.e. the binding properties.
- The ability to dissolve some of the inorganic components produces a "cleaner" solid fuel with respect to removal of some of the inorganic content; an advantage that is highly beneficial in combustion and gasification processes.

A PhD study in STOP has been solely focusing on the topic wet torrefaction. Different aspects of product enhancements and applicability have been studied and published throughout the course of the project.

A list of all publications can be found at the end of this handbook.



Grinding is much easier after torrefaction.

Plant advantages

Before starting to talk about the advantages of using torrefied materials one has to be observant of the fact that there is a certain increase in fuel cost associated with this type of fuel pretreatment. This cost can be reclaimed if transport costs of the biomass and plant costs savings are taken into account. Quantifications of such savings can be estimated for carefully chosen scenarios. The extent of these savings will depend on many factors and should be evaluated separately for the specific cases.

Other advantages that will not have a direct influence on the costs are more difficult to assess. However, they can introduce some real advantages to the overall plant performance and should also be taken into account while considering this pretreatment step in existing processes.

As an example, the ability to resist biodegradability is a property that should not be taken lightly as it results in an extended storage period for the biomass and reduces the quality requirements of the storage facility in itself. Also outdoor storage of torrefied material could be a possibility.

There are three main thermal processes that are relevant in terms of torrefied material usage. These are combustion, co-firing and gasification.

Combustion

Through the STOP project we studied the combustion efficiency and polluting emissions of raw and torrefied biomass in a pellet stove combustor for residential heating.

One important finding was that technology should be modified in order to perform optimally with a fuel torrefied at a high temperature. This is most critical for micro scale installations such as pellet stove combustors. For larger scale plants, e. g. grate combustion plants, operating conditions tweaking will probably be sufficient.

For the pellet stove combustor, we were able to reduce both the emissions of particles and the products of incomplete combustion when burning mildly torrefied pellets; torrefied at 225 ^{O}C.

More importantly, the emission numbers were in favor of the torrefied fuel also when setting the combustor to a low load, i.e. part load operation.

Usually, such appliances perform poorly at low part load, which has become the normal method of operation in modern houses with reduced heating requirements.

Grate combustion of torrefied material at a larger scale has not been carried out within the STOP project, mainly because we do not have a torrefaction facility that is capable of producing torrefied fuels for such a large scale. However, stability improvements can be foreseen by looking at the main challenges of such a technology.

Often grate combustion technologies are tormented by process instabilities caused by variations in fuel quality and moisture content. The process is not able to respond in good time to such variations and ends up operating at conditions that are far from optimal, which results in increased emissions. The homogeneity of torrefied biomass and its narrow range of moisture content are among the properties that help reduce combustion inefficiencies. The reduced moisture and volatile content also result in reduced flue gas volumes and by that lower cost for flue gas cleaning.

Co-firing

Co-firing is a technology that has been adopted lately as an intermediate solution for reducing the CO_2 emissions caused by coal combustion.

The idea is to replace part of the coal in existing large scale plants with the sustainable alternative, i.e. biomass. In such facilities, coal is combusted using dust burners which are known for their efficiency because of the high level of mixing attained between combustion air and the very small coal particles.

Biomass needs to be grinded to smaller particles in order to be able to mix it directly with coal, for combustion in the same burner. Grinding biomass down to such a particle size requires so much energy that it becomes economically unfeasible.

Another problem is the fibrous structure of biomass which will result in a thread-like particle shape after milling. These long threaded particles have shown to be difficult to combust along with coal in dust burners.

By applying torrefaction, the structure of the wood is modified, provoking modifications of its properties. The hemicellulose which acts as “glue” for the cellulose is broken down, weakening the physical structure of the biomass. The result is a brittle product that requires much less energy to grind and the loss of fibrous structure after which the particles become more spherical in shape. The new coal-like particles are easily mixed and combusted with coal in these dust burners.

Gasification

Gasification is looked upon as the more flexible energy conversion alternative as the variety of syngas qualities that is produced can be upgraded or converted to almost any energy carrier one can think of.

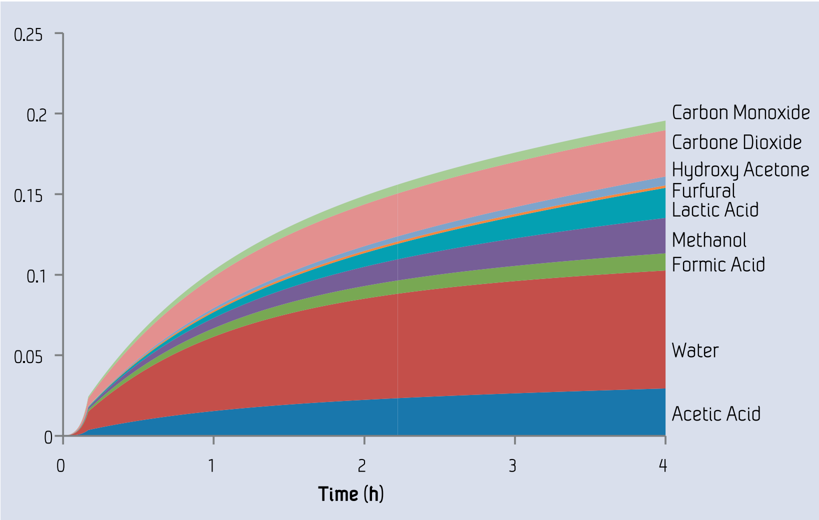
One specific route that has been discussed and considered promising by many is the production of liquid transport fuels from biomass, a CO_2 neutral source. More specifically, biomass to liquid conversion through a Fischer–Tropsch process (FT) looks to be promising given that the challenges related to this process are resolved. The same technology for coal, using an entrained flow reactor for the gasification, has been available commercially for quite some time now.

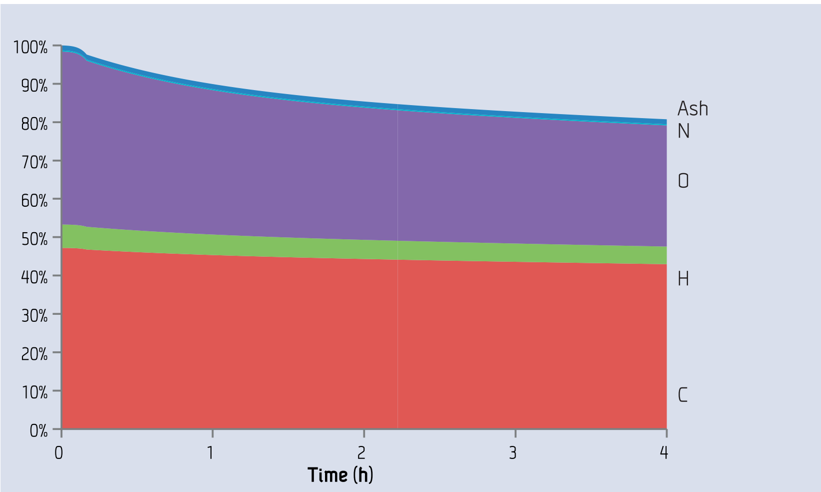
Porting this technology to biomass has not been easy so far due challenges related to fuel heterogeneity and particle entrainment properties. Most of these challenges can be solved through torrefaction in such a manner that have been explained under the chapter “co-firing”.

Another argument that might tip the balance even more in favor of torrefied fuel is savings made during fuel transport due to the higher volumetric energy density of a compacted torrefied fuel, e.g. pellets. This is especially important for biomass to liquid processes based on FT which need to be quite large in scale to be economically feasible. At such a scale the biomass transport cost can take up a significant share of the total plant operating cost so that optimizing this step must also be considered.

Stable operating conditions lead to better efficiency and less emission.

Modeling torrefaction





Modeling is an important tool that can be applied for the prediction of fuel behavior during thermal treatment.

Answers to questions like, how fast reactions can one expect for a given fuel type when temperature and/or the residence time increase, can easily be deduced by performing a series of thermogravimetric experiments. Being able to predict this will help at the design stage of the torrefaction technology.

More importantly, the properties of the pretreated fuels can also be predicted as a function of torrefaction severity. This is quite useful for the industry and can help determine the correct parameters at which the raw fuel should be treated for optimal performance in an energy conversion plant.

In the figures to the left we see the modeled changes in the element composition (lower figure) and the mass fraction released as volatiles (upper figure) for spruce, kept at 250 ^{O}C for 4 hours.

Torrefaction costs

The advantages of torrefaction have been discussed in details throughout this handbook. These are obviously advantages of such an importance that they can have quite an impact during thermal conversion.

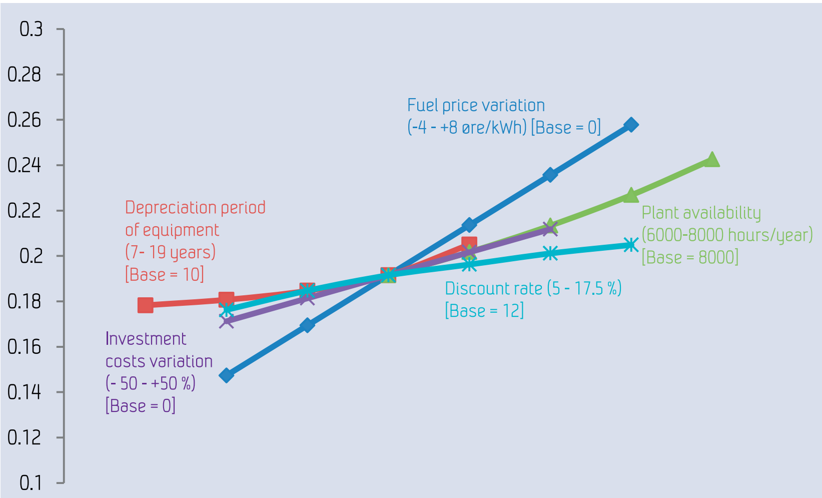
However, no matter how good these advantages are, if the pretreatment cost is a predominant factor of the overall costs, it will not be economically feasible. Therefore, during the course of the STOP project an attempt was made to estimate the production costs of torrefied material.

Calculations were based on a factorial method that aims at estimating the capital investment costs first and subsequently the total production costs. In order to perform these calculations, the energy efficiency of the torrefaction process was calculated using the process simulation tool Aspen Plus. The input for the energy calculations were collected from an earlier experimental investigation performed in our laboratory.

The assumptions and parametric variations were as follows:

- Fuel: Birch
- Moisture content: 20 – 50 wt%
- Moisture content after drier: 15 wt%
- Plant capacity: 40 – 120 MW
- Utility fuel: Natural gas
- Flue gas stack temperature: 120 °C
- 10 % heat losses overall

A sensitivity analysis of the production costs in øre/kWh for some chosen parameters is shown in the figure to the right. The range of parameter variations is shown in the parentheses in the legend while values used in the base case scenario are shown in the brackets (the base case is the point in the figure where all the lines intersect). Among the chosen variation ranges, we notice that the fuel price has most influence on the production costs followed by plant availability. Parameters that have less influence on the production costs are variations in investment costs and discount rate.



Torrefaction reactor

The recipe to better fuel starts with torrefaction.

A torrefaction reactor was designed and financed (as a part of own strategic investments) by SINTEF Energy Research and its construction was contracted to an external company.

The reactor has been operational in our laboratory since 2011 and has been used to study the torrefaction process and to produce fuel for further studies.

Not only the STOP project has benefited from this, but also other SINTEF projects, among these are GasBio and CenBio. Samples produced in our laboratory have travelled as far as Sandia National Laboratories in the USA and IREC (The Catalonia Institute for Energy Research) in Spain.

The torrefaction reactor is composed of different horizontal screw conveyors positioned on top of each other. The pellets are stored in a fuel bin at the top of the reactor and first go through a feeding screw, followed by separate conveyors for drying, heating, torrefaction and cooling, before they finally fall into a product container. The conveyors are temperature controlled using electrical heating elements, with the exception of the water cooled cooling conveyor. All parts of the reactor (including the storage bin and the product container) can be purged with separate streams of N_2 in order to ensure inert conditions during operation. The pellets are transported in between the conveyors using pneumatically controlled sliding valves.

Recommendations for a successful implementation

- from a Norwegian perspective

The total energy conversion based on biomass in Norway is estimated to ca. 17.5 TWh (SSB, 2012). The above number is an estimate that also includes fractions that are irrelevant for torrefaction such as municipal solid waste, bio-oil and bio-gas.

The main energy conversion that is based on wood is distributed as follows:

- Private households (mainly residential heating through wood stoves) 7.3 TWh
- Industry 5.5 TWh (3.7 TWh of this comes primarily from the wood processing industry)
- Plants for heat and CHP 1.5 TWh

From the above distribution we can see that the biggest contribution comes from wood stoves.

The traditional wood stove depends on wood logs, which will not be suitable for torrefaction because of its large size. However, we have already seen, as part of the STOP project, that pellet combustors benefit from mildly torrefied wood pellets.

Pellet combustors, on the other hand, are still not the first choice for the Norwegian consumer due to the higher investment cost for this appliance compared to the normal wood stove. The clear advantage of the pellet stove lies however in the large decrease of the particle emission compared to a wood stove, which is further improved with torrefied wood pellets. This means that one can expect an improvement in the air quality if wood stoves are to be replaced with pellet stoves, a fact that will definitely result in savings in medical treatment and

Torrefied pellets can be used in a wide range of conversion technologies.

a prolonged life expectancy for people living in urban areas or in close proximity to households using these heating methods.

It is nevertheless up to the government to decide if such savings are worth pursuing through incentives that will make pellet stoves more competitive.

In other words the market for producing torrefied pellets in Norway is currently non-existent but can become a reality with a little political help.

The second largest biomass consumer is the industry with an annual production of 5.5 TWh. This is usually an energy form that is used by the industry itself and is based on a feedstock that is a byproduct from their industrial process.

An example is the wood processing industry that typically produces sawdust that is used onsite for energy purposes. This fraction will most likely be unavailable for torrefaction.

The third main consumers of woody biomass are producers of heat (mainly) and electrical power (a relatively small portion). These are distributed across Norway in the form of energy plants mainly connected to the district heating grid.

Usually plants operators/owners are not research focused and are confined to feedstocks that are available for the Norwegian market.

As always, the main drivers profitability and operational improvements are usually influenced by changes in the governmental emission regulations.

There should be a potential for increased profitability for some of the plants, which can be gained through improved operational stability and increased efficiency. This can be attained by using more advanced fuels such as torrefied biomass.

However, an accurate prediction can only be made through a case by case study.

Operators that have instability problems in their operation should consider using torrefied biomass or as well the integration of torrefaction as a pretreatment method in their respective plants.

Publications

Journal publications

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The "dream fuel" is already here!
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CO_2 gasification of chars prepared from torrefied wood. To be submitted to Energy & Fuels.
Liang Wang, Roger A. Khalil, Gabor Várhegyi, Øyvind Skreiberg.

Reactivities of wet torrefied Norwegian biomass fuels in oxidative environment. To be submitted to Energy & Fuels.
Quang-Vu Bach, Khanh-Quang Tran, Roger A. Khalil, Øyvind Skreiberg.

Torrefaction influence on pelletability and pellet quality of Norwegian forest residues. To be submitted to Energy & Fuels.
Nevena Mišljenović, Quang-Vu Bach, Khanh-Quang Tran, Carlos Salas-Bringas, Øyvind Skreiberg.

Pyrolysis kinetics of wet torrefied softwood and hardwood. To be submitted to an international journal.
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Wet torrefaction of forest residues. Abstract submitted to ICAE2014.
Quang-Vu Bach, Khanh-Quang Tran, Roger A. Khalil, Øyvind Skreiberg.

Torrefaction kinetics of Norwegian biomass fuels. Abstract submitted to iconBM2014.
Quang-Vu Bach, Khanh-Quang Tran, Roger A. Khalil, Øyvind Skreiberg.

Torrefaction is a thermal pretreatment method for inhomogeneous and raw biomass fuels upgrading these to higher value fuels with enhanced transport (as pellets), feeding (as pellets or powder) and thermal conversion properties, giving stable and improved operating conditions and reduced emissions in thermal conversion units (from pellet stoves to co-firing plants) producing heat or heat and power.

Torrefaction,
a biomass contribution towards our sustainable energy future!

STOP - STable OPerating conditions for biomass combustion plants

Industry partners:

Akershus Energi AS, Norges Skogeierforbund, NTE Holding AS, Hafslund ASA, Statkraft Varme AS, Norsk Protein AS, Norges Bondelag, Oslo Kommune Energigjenvinningsetaten, Vattenfall AB Nordic Heat, Energos AS, Cambi AS, Jøtul AS and Granit Kleber AS

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