Optimization of product specific processing parameters for the production of fuel pellets from torrefied biomass

Resultat-Kontrakt (RK) Report

Wolfgang Stelte

Danish Technological Institute

Center for Biomass and Biorefinery

Gregersensvej, 2630 Taastrup, Denmark

Introduction

Heat and power production from renewable biomass resources is an increasing business sector and has resulted in a strong growth of global biomass trade, in particular biomass pellets [1]. Lignocellulosic biomass has compared to conventional fuels a relatively low bulk and energy density and a low degree of homogeneity. Thermal pre-treatment technologies such as torrefaction, are applied to improve the fuel properties of biomass i.e. less water and oxygen in the fuel, favorable milling properties, storage properties [2,3].

During torrefaction the biomass is roasted in an oxygen-depleted environment at temperatures between 240 and 320 °C. During torrefaction moisture and low molecular weight volatiles are removed from the biomass, resulting in a product with low O/C and H/C atomic ratios [2,4,5]. The mechanical properties of the fibers are altered during the thermal treatment due to the thermal degradation of the biomass polymers i.e. lignin, hemicellulose and cellulose, transforming the fibers into a brittle and partly hydrophobic material [2,4]. To improve the handling properties of torrefied biomass, torrefaction is usually combined with pelletization or briquetting operations. The aim is to produce a durable and water resistant energy carrier that ideally can be used in existing conveying and storage facilities designed for hard coal, making them an ideal replacement for coal in existing heat and power plants [2,6].

Pellets made from torrefied biomass have a higher energy density per volume compared to established biofuels such as wood chips or wood pellets, resulting in lower transportation and storage costs. In case of torrefied wood, the bulk density can be increased from 200-400 kg/m^3 for the torrefied wood chips to about 600-850 kg/m^3 for torrefied pellets [2,4] depending on species and processing conditions. An overview of the fuel properties and a comparison to other solid biofuels is shown in Table 1.

Table 1. Properties of wood, torrefied biomass and pellets [2,4].

Properties	Unit	Wood	Torrefied Biomass	Wood pellet		Torrefied Pellets	
				Low	High	Low	High
Moisture	%wt	35	3	10	7	5	1
LHV							
- **normal**	MJ/kg	10.5	19.9	15.6	16.2	19.9	21.6
- **dry**	MJ/kg	17.7	20.4	17.7	17.7	20.4	22.7
Mass density	Kg/m^3	550	230	500	650	750	850
Energy density	GJ/m^3	5.8	4.6	7.8	10.5	14.9	18.4

The standardized shape and size of pellets and briquettes is an advantage for the trade and process automation since potentially hazardous dust is removed from torrefied biomass during densification operations. Dust emissions from pellets and briquettes during loading, un-loading and conveying operations are much lower than for the loose biomass. Densification is therefore considered as an indispensable process operation to meet the end-users quality demands for a stable, safe and easy to handle product.

While pelletization of biomass is considered an established technology, torrefaction is still a rather new technology for the production of solid energy carriers. Technological development has made significant progress during the past decade. However, pellets made from torrefied biomass are not established as a commodity fuel yet.

Process optimization of torrefaction and densification processes

Biomass Torrefaction

Different types of torrefaction technology have been developed during the past decade and are illustrated in Figure 1.

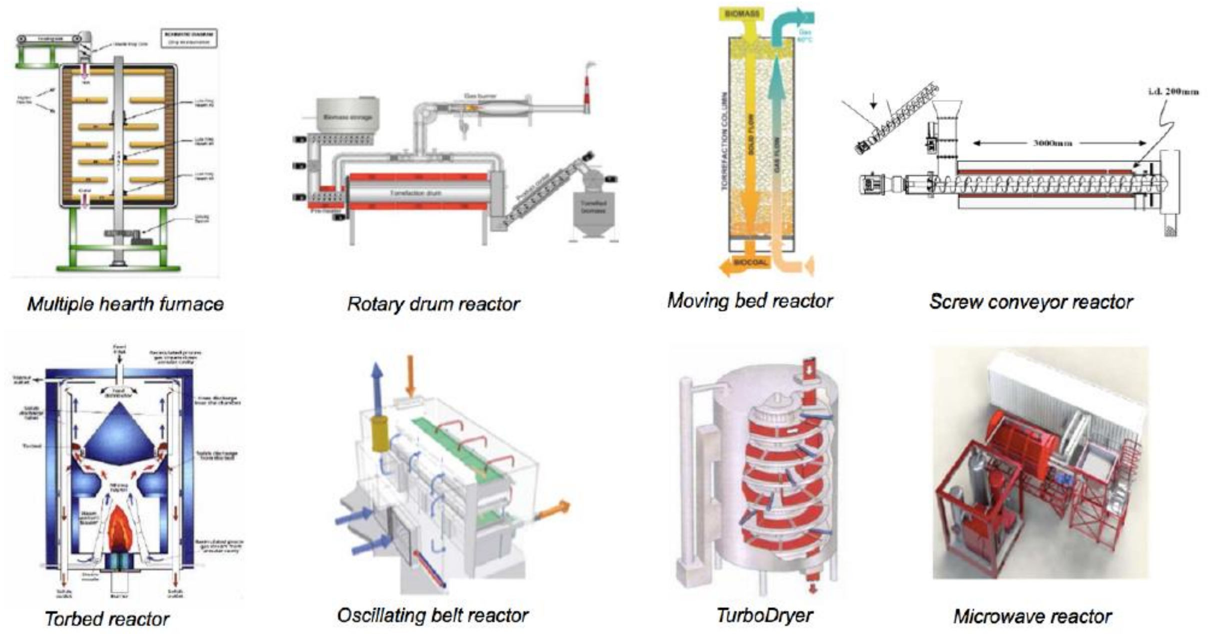

Figure 1. Different torrefaction technologies [7]

The technologies differ by the orientation of the reactor and operation modes. The pros and cons of the different reactor types have been reviewed recently by Mościcki et al. [8] The technologies have in common that solid biomass is heated in an oxygen depleted atmosphere to a target temperature for a defined period while conveying the biomass trough the reactor body. Key processing parameters are the reaction temperature and retention time that define the degree of torrefaction of the biomass.

The physical properties of the torrefied biomass depend to large extend on the torrefaction conditions i.e. reaction time and temperature. The three main components of lignocellulosic biomass, lignin, cellulose and hemicellulose, are broken down and altered during torrefaction by depolymerization, recondensation and carbonization reactions as illustrated in Figure 2.

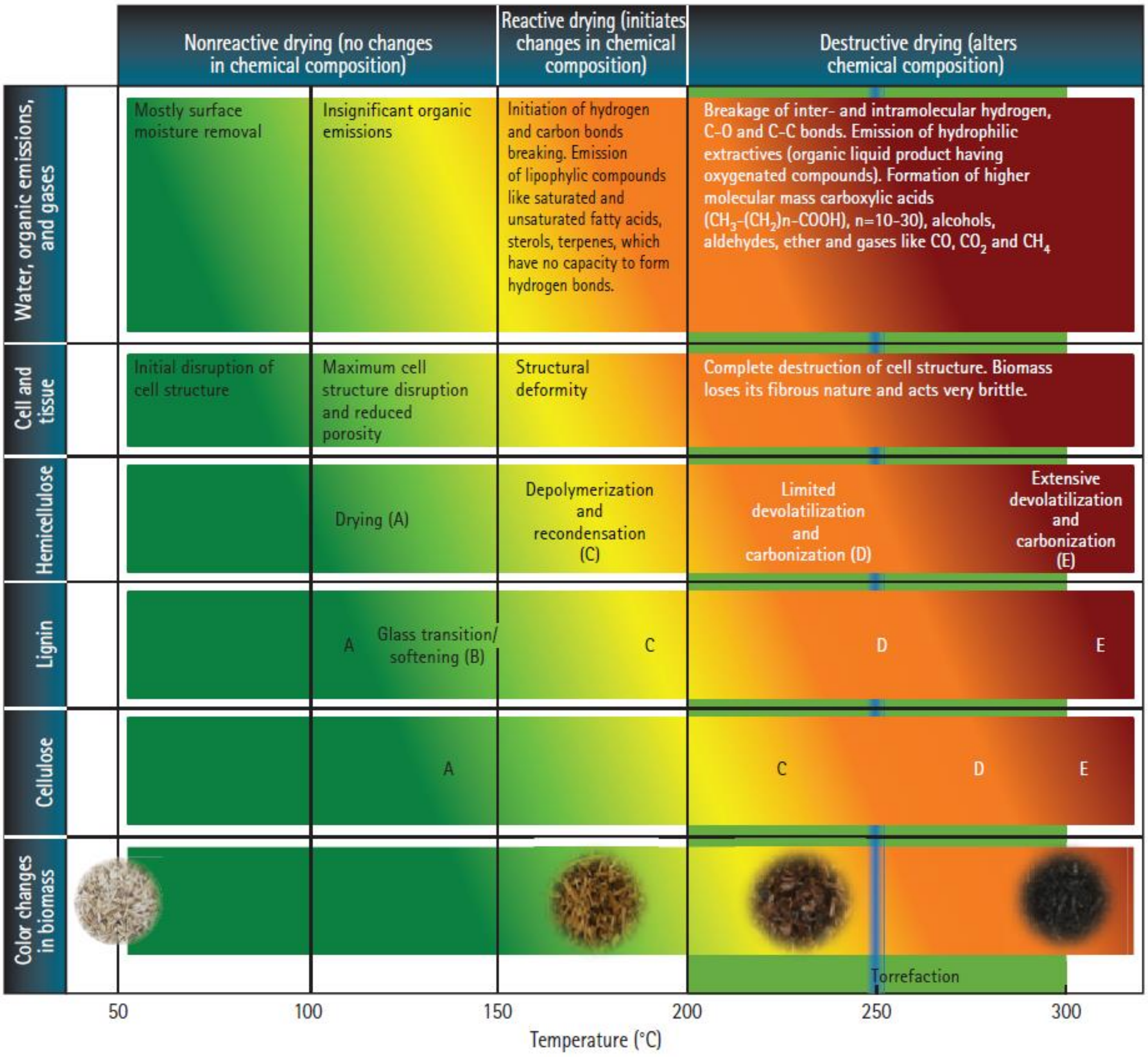

Figure 2. Structural, chemical, and color changes in lignocellulosic biomass during torrefaction. A: Drying, B: Softening/Glass transition, C: Depolymerization and recondensation, D: Limited devolatilization and carbonization, E: Extensive devolatilization and carbonization.

The torrefaction process and its processing parameters result in different degrees of torrefaction that have a significant impact on the fuel properties of the material such as densification properties, safety and storage aspects, grindability and heating value as illustrated as indicative trends in Figure 3.

Process optimization has to be made towards finding the optimal degree of torrefaction with respect to its fuel properties and will always be a trade-off between the different product characteristics.

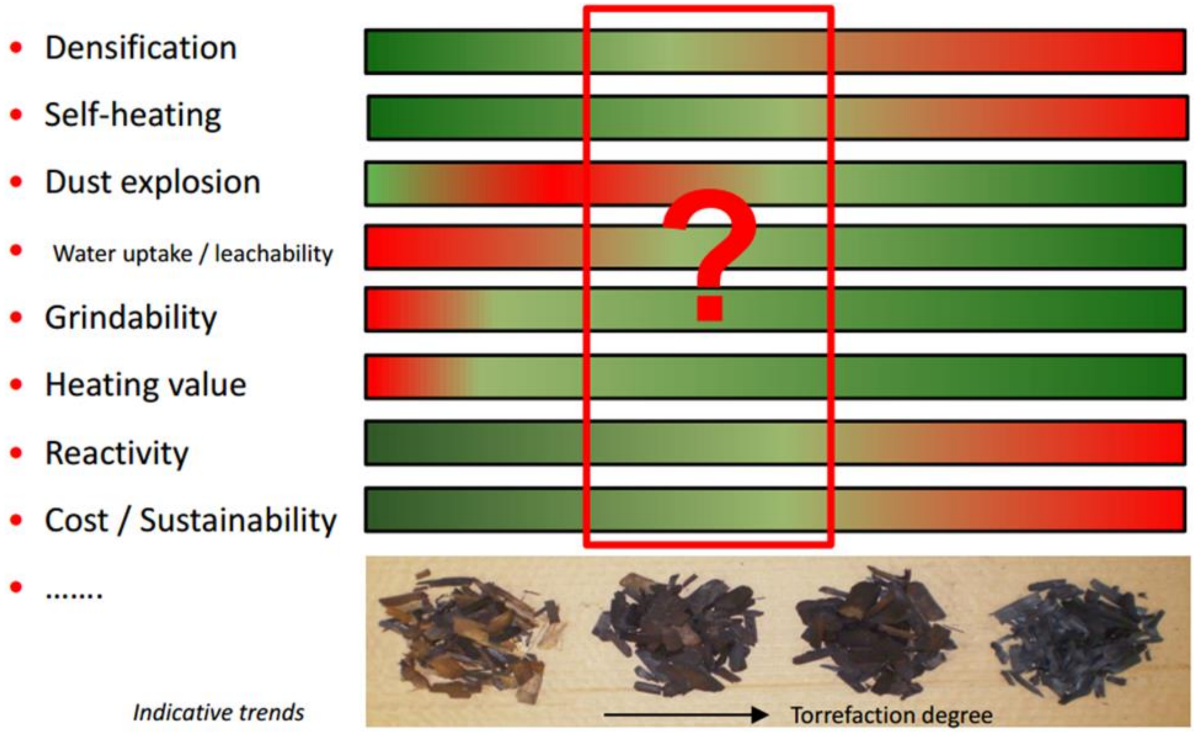

Figure 3. Impact of torrefaction degree on the fuel properties of torrefied biomass [10].

Biomass pelletization

The alteration of the physical and chemical characteristics has a significant impact on the subsequent densification processes i.e. pelletization and briquetting.

Although pelletization and briquetting of lignocellulosic biomass are established and well known processes the pelletization of torrefied biomass has for long time been an underestimated bottleneck in the production process for torrefied energy carriers and a fall-string in the process development and commercialization for many torrefaction initiatives and start-up companies.

The production processes applied to produce conventional wood pellets cannot be applied directly onto torrefied biomass. Major challenges that had to be overcome where a significantly higher energy uptake of the pellet press due to high friction and low pellet quality.

The densification of torrefied biomass into pellets and briquettes has been under investigation for the past decade by industry and research institutions and significant progress has been made with respect to product quality and economy.

To understand what is lying behind those difficulties and how they were solved, it is important to look on how the pelletizing process "normally" works for conventional biomass and how it has to be adapted so it will work for torrefied biomass.

Biomass is pelletized in pellet mills where the biomass is fed into press channels of defined length and diameter and exposed to high pressures and frictional heat as illustrated in Figure 4.

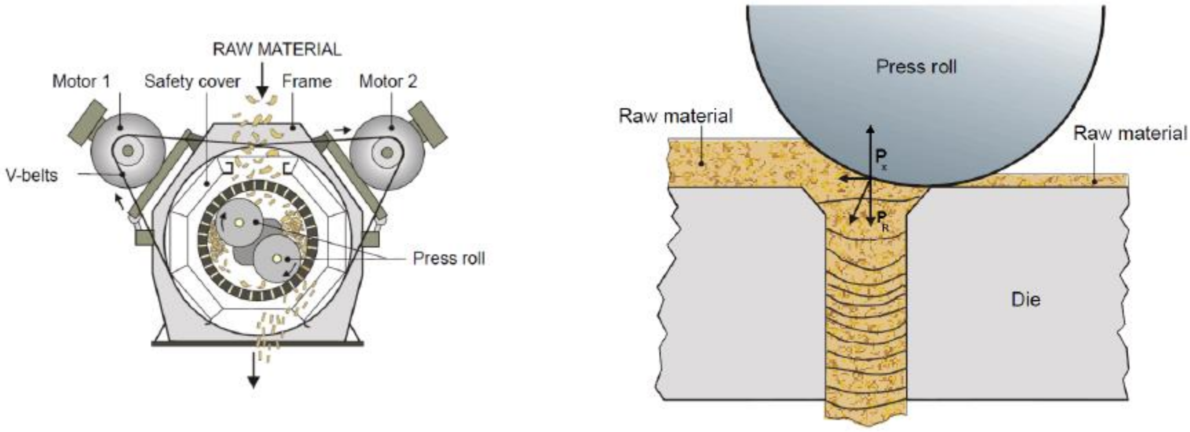

Figure 4. Illustration of the pelletizing process [11,12]

Heat and pressure in combination with moisture, present in the biomass, result in a softening and flow of the biomass polymers, here especially the lignin. The polymer chains of the lignin from different particles flow and begin to interpenetrate each other. Due to the high pressure, the particles in a pellet are brought into very close proximity, enabling the formation of an inter-particle network of molten lignin polymer that solidifies upon cooling, forming solid inter-particle bridges that keep the pellet together [13]. Other important forces keeping a pellet together are hydrogen bonds between polymer chains of adjacent particles in a pellet, fibre interlocking as well as cohesion and adhesion forces [12].

These bonding mechanisms are hampered by the torrefaction process. The high friction and low pellet quality observed when pelletizing torrefied biomass is a consequence of the thermal degradation of the biopolymers (hemicellulose, cellulose and lignin) resulting in a destruction of the fibrous structure and tenacity of the biomass. Hydrogen and oxygen are removed from the biomass in dehydration and condensation reactions, resulting in an increasing inability of the biomass to bind water and to form hydrogen bonds [14]. The softening temperature (glass transition temperature) of the remaining lignin likely shifts to higher temperatures and the number of potential hydrogen bonding sites (one of the key forces holding a pellet together) is reduced, resulting in less bonds between the particles in a pellet and consequently to lower pellet strength and durability.

Another consequence that has not been totally understood yet is the increase of the friction coefficient between the particles and the press channel, but also between the torrefied biomass particles itself that results in an increased energy uptake of the pellet mill as well as wear on the machinery and excessive friction heat.

Optimization of processing parameters

A lot of progress has been made in optimizing torrefaction and densification processes during the past five years and according to the torrefaction industry resulted in mature production processes [15].

Numerous initiative within the torrefaction industry as well as international research projects (EU-projects SECTOR, LogistEC) and research groups around the world have been working with the optimization of densification processes of torrefied biomass during the past ten years. Elaborated studies and experimental designs, pilot and production scale optimizations have incrementally increased the knowledge of torrefaction and densification operations and finally resulted in the development of mature production processes

First attempts resulted in the use of additives to improve the pellet strength and lower the friction. Different substances such as lignin, starch, oils, torrefaction condensate, etc. have been used. While it was possible to reduce friction or increase the pellet strength it remained a challenge to find an additive that can serve both purposes decrease friction and improve pellet quality [16].

Key process parameters that have been identified for the pelletization of biomass were: Species, particle size, moisture content, conditioning temperature, pelletizer temperature, die length and diameter, die rotation speed [17,18] and in case of torrefied biomass especially the degree of torrefaction [19-21].

Unfortunately there is no “simple recipe” how to pelletize torrefied biomass valid for all biomass species and torrefaction degrees. Most common problems when pelletizing torrefied biomass were high energy consumption due to high friction build up in the press channels of a pellet mill, in worst case resulting in fire or blocking of the press channels. Another common problem is an instable and often poor product quality i.e. short pellets, low durability and dust) in worst case no pellets are formed and only dust is obtained as a product from the pellet mill.

Different strategies have been applied to counteract the negative effects of torrefaction on the pelletizing process such increasing the die temperature, adding water to the torrefied biomass, use of binders and lubricants [19-21]. There is also a mutual correlation between torrefaction and densification parameters that needs to be taken into account for process optimization [22,23].

Feedstock

For the feedstock species it can generally be said that torrefied hardwoods are easier to pelletize then torrefied softwoods [24]. Poplar is an example of a raw material that can easily be pelletized after torrefaction also at high degrees of torrefaction. Other raw materials such as torrefied spruce, pine, bamboo or wheat straw require a delicate balance of the pelletizing parameters such as moisture addition, press channel diameter and length, rotation speed, particle size etc. Some materials such as torrefied bark have been found to be “impossible” to pelletize [25]

Degree of torrefaction

The degree of torrefaction is a measure for the severity of the torrefaction process and measured as biomass yield after torrefaction. The lower the yield the more severe was the torrefaction process resulting in greater mass loss. The degree of torrefaction is a function of torrefaction temperature and time. An increasing torrefaction degree makes the pelletizing process more difficult resulting in increasing friction and thus an increasing power consumption. Furthermore is the pellet quality heavily affected by the degree of torrefaction. The thermal degradation of the biomass polymers, especially the loss of hydrogen and oxygen from the biomass, prevents the formation of interparticle bonding, and thus reduces the mechanical properties of the pellet. This effect can be compensated by adding moisture to the torrefied biomass prior pelletization and by increasing the temperature of the pelletizing die [21,11].

Temperature

The temperature of the pelletizing die is usually a product of the friction generated in the press channels of a pellet die and only some advanced, experimental set-ups allow a controlled heating or cooling. The friction in a pellet can be lowered by changing the die dimensions (i.e. length, diameter) [26] as well as moisture addition to the torrefied biomass before pelletization [21,22]. The softening temperature (glass transition temperature) of lignin likely increases during the torrefaction process due to the removal of moisture from the biomass. Increasing the pelletizing temperature compensates for the upwards shift of the softening temperature of the lignin due to torrefaction and will likely result in better bonding. Different studies have indicated that temperature increase results in better pellet quality and less friction during pelletization. [16,22]. A too high pelletizing temperature close or above the torrefaction temperature bears the risk for thermal decomposition and further exothermal reactions.

Moisture addition

Moisture has been shown to lower both friction and improve the strength of torrefied pellets [16,22]. It has been reported that 10-20 % moisture added to the dry torrefied biomass before pelletization improve the pelletizing properties significantly. Water has been shown to act as a plasticizer, reducing the softening temperature of lignin in pellet production and thus promoting the formation of an inter-particle network of molten and solidified lignin [14,27]. In case of too high moisture levels the evaporation of water from the biomass in the hot die during pelletization could result in pressure increase and steam explosion within the pellet die with a negative effect on the pellet quality. Water with its high heat capacity is also an excellent medium to remove friction heat from the process. Water content is therefore a very important and delicate to adjust process parameter.

Die dimensions

Length and diameter of the dies is one of the most crucial parameters for biomass pelletization. The pressure generated by friction in the press channel of a pellet die is exponentially correlated to the length of a press channel and has therefore a great impact on the energy uptake of a pellet mill and wear on the equipment. Within the EU research project SECTOR (Solid sustainable energy carriers by means of torrefaction) [28] pellet diameters between 4 and 12 mm have been tested and best results with respect to pellet quality, capacity and energy uptake have been obtained between 6-8 mm diameters. There are different theories how the pellet diameter may affect the friction and the pellet quality. Small diameters result in an increased surface to volume ration and provide a better transport of heat into and out of the pellet. There is friction between the biomass particles within a pellet as well as between the press channel wall and the particles at the outside of the pellet. A smaller diameter will increase the surface and the number of particles touching the metal surface. It is not yet fully understood why in some cases small pellet diameters result in lower friction and better quality while in other cases it does not.

Die rotation speed

Results from the EU research project SECTOR (Solid sustainable energy carriers by means of torrefaction) [28] indicate that the rotation speed of the die has been shown to be correlated to pellet quality that is increasing when decreasing the rotation speed of the die. The slower rotation results in a longer retention time of the pellets in the die while they are still under pressure and that may result in an improved softening and flow of polymers, forming an inter-particle network with more links and better stability as for pellets that are produced in half of the time. The capacity of the pellet mill is however negatively affected and an optimum tradeoff has to be found.

Briquetting as an alternative to pelletization

Generally, it can be said that briquetting is a less complex process that can more easily be adapted to different feedstocks including torrefied biomass. The problems to be solved were similar to pelletization i.e. high friction resulting in heat development and higher energy uptake as well as low briquette quality due to poor inter-particle bonding Briquetting of torrefied biomass has been improved by the adjustment of the moisture content and optimization of die temperature and time the briquette is kept under pressure subsequent to the briquetting process i.e. in a cooling conveyer. [29].

Different studies have been made to map the correlation between torrefaction and densification parameters and their influence on the resulting pellet quality [22,23].

Results have shown that there is a narrow process window to optimize the pellet quality by trading off torrefaction and pelletization parameters such as degree of torrefaction and moisture content [22].

References

[1] Goh, C. S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., Heinimö, J., Deutmeyer, M. (2013). Wood pellet market and trade: A global perspective. Biofuels, Bioproducts and Biorefining, 7(1), 24-42.

[2] Van der Stelt, M. J. C., Gerhauser, H., Kiel, J. H. A., & Ptasinski, K. J. (2011). Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass and Bioenergy, 35(9), 3748-3762.

[3] Uslu, A., Faaij, A. P., & Bergman, P. C. A. (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy, 33(8), 1206-1223.

[4] Bergman, P.C.A. (2005) Combined torrefaction and pelletisation: the TOP process. Report ECN-C-05-073. Petten, The Netherlands: ECN.

[5] Lestander, T. A., Rudolfsson, M., Pommer, L., Nordin, A. (2014). NIR provides excellent predictions of properties of biocoal from torrefaction and pyrolysis of biomass. Green Chemistry, 16(12), 4906-4913.

[6] Koppejan, J., Sokhansanj, S., Melin, S., Madrali, S. (2012). Status overview of torrefaction technologies. In IEA bioenergy task (Vol. 32).

[7] Gårdbro G (2014). Techno-economic modeling of the supply chain for torrefied biomass. Master Thesis from Umeå University - Institution Department of Applied Physics and Electronics.

[8] Mościcki, K. J., Niedźwiecki, Ł., Owczarek, P., & Wnukowski, M. (2014). Commoditization of biomass: dry torrefaction and pelletization - a review. Journal of Power Technologies, 94(4), 233-249.

[9] Shankar Tumuluru, J., Sokhansanj, S., Hess, J. R., Wright, C. T., & Boardman, R. D. (2011). REVIEW: A review on biomass torrefaction process and product properties for energy applications. Industrial Biotechnology, 7(5), 384-401.

[10] Kiel, J. Torrefaction – product quality optimisation in view of logistics and end-use. Presented at:

World Biomass Power Markets, 17. May 2013, Amsterdam.

[11] Alakangas, E., Paju, P. (2002) Wood pellets in Finland. OPET 5 Report, VTT Technical Research Centre of Finland.

[12] Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012). Recent developments in biomass pelletization–A review. BioResources, 7(3), 4451-4490.

[13] Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., & Henriksen, U. B. (2011). A study of bonding and failure mechanisms in fuel pellets from different biomass resources. *Biomass and bioenergy*, *35*(2), 910-918.

[14] Stelte, W., Nielsen, N. P. K., Hansen, H. O., Dahl, J., Shang, L., & Sanadi, A. R. (2013). Pelletizing properties of torrefied wheat straw. Biomass and Bioenergy, 49, 214-221.

[15] Michael Wild (2014) "Torrefaction – International Overview of Developments in this novel Technology" Presentation at the IEA Bioenergy Task 32 and Task 40 workshop, Central European Biomass Conference, 17. January 2014, Graz, Austria.

[16] Stelte, W., Dahl, J., Nielsen N.P.K., Hansen, H.O. (2012) Approach and progress in relation to challenges with pelletization of torrefied biomass. Oral presentation at the 20th European Biomass Conference. Milan, Italy, 18-22. June 2012.

[17] Samson, R., Duxbury, P., Drisdelle, M., & Lapointe, C. (2000). Assessment of pelletized biofuels. Publication at: http://www. reap-canada. com/Reports/pelletaug2000. html.

[18] Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., & Henriksen, U. B. (2011). Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. Fuel, 90(11), 3285-3290.

[19] Stelte, W., Clemons, C., Holm, J. K., Sanadi, A. R., Ahrenfeldt, J., Shang, L., Henriksen, U. B. (2011). Pelletizing properties of torrefied spruce. biomass and bioenergy, 35(11), 4690-4698.

[20] Na, B. I., Kim, Y. H., Lim, W. S., Lee, S. M., Lee, H. W., & Lee, J. W. (2013). Torrefaction of oil palm mesocarp fiber and their effect on pelletizing. Biomass and Bioenergy, 52, 159-165.

[21] Larsson, S. H., Rudolfsson, M., Nordwaeger, M., Olofsson, I., & Samuelsson, R. (2013). Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. Applied Energy, 102, 827-832.

[22] Rudolfsson, M., Stelte, W., & Lestander, T. A. (2015). Process optimization of combined biomass torrefaction and pelletization for fuel pellet production–A parametric study. Applied Energy, 140, 378-384.

[23] Misljenovic, N., Bach, Q. V., Tran, K. Q., Salas-Bringas, C., & Skreiberg, Ø. (2014). Torrefaction Influence on Pelletability and Pellet Quality of Norwegian Forest Residues. Energy & Fuels, 28(4), 2554-2561.

[24] Klaus Trattner (2014) Andritz Torrefaction Technologies - Summary of pilot plant operation in Austria and Denmark. Presentation at the IEA Bioenergy Task 32 and Task 40 workshop, Central European Biomass Conference, 17. January 2014, Graz, Austria.

[25] Carl Wilén, Perttu Jukola, Timo Järvinen, Kai Sipilä, Fred Verhoeff, and Jaap Kiel (2013) “Wood torrefaction–pilot tests and utilisation prospects” Technology Report 122, VTT Technical Research Centre of Finland, Espoo, Finland.

[26] Nhuchhen, D. R., Basu, P., & Acharya, B. (2014). A Comprehensive Review on Biomass Torrefaction. International Journal of Renewable Energy and Biofuels, 2014, i1-56.

[27] Stelte, W., Clemons, C., Holm, J. K., Ahrenfeldt, J., Henriksen, U. B., & Sanadi, A. R. (2011). Thermal transitions of the amorphous polymers in wheat straw. Industrial Crops and products, 34(1), 1053-1056.

[28] EU Research project SECTOR: https://sector-project.eu

[29] Stelte W, Nielsen NPK, Nielsen MRA, Knudsen MS. Production scale briquetting of torrefied biomass. Oral presentation at European Biomass Conference, Copenhagen, Denmark 3-7. June 2013.