Report STSM in Foulum campus of Aarhus University, (Denmark) occurring between 03-04-2017 to 07-04-2017

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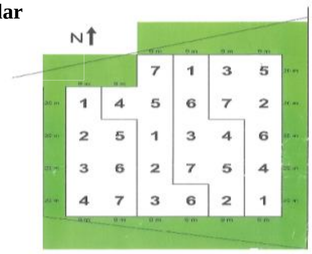
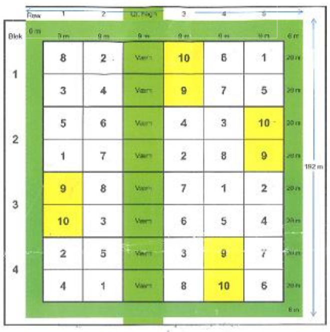
As scheduled this STSM in Denmark occurred in the period between 03-04-2016 and 07-04-2017. The STSM was set in two stages. For convenience of Dr. Poul Laerke and Dr. Uffe Jorgensen of Aarhus University, the analysis of the relevant experimental trials of willow and poplar in the Foulum campus was made in April 6 and April 7. This field analysis was dedicated to the appreciation of the experimental plots of willow and poplar SRCs for evaluation how the interactions among environmental, management and genetic factors affect biomass yield. The willow plots were established in the context of a wider experiment begun in May 2010 in a set of five locations in Denmark: Foulum, Jyndevad, Hojmark, Foerson and Odum. The trial in Jyndvad was located in the Southern Jutland island, whereas the other four were located in Center Jutland. Foulum and Jyndevad sites were established by Aarhus University research department and the other three sites were part of a network of commercial grown willow fields. In Foulum, the trial was established under a randomized block design with 40 plots. The standard density in all plots was 12000 cuttings ha^{-1}. The geometry of the plots was a five double row scheme with a total experimental area of 192 m length and 54 m width (Fig. 1b). Each plot comprised 4 double rows, corresponding to 9m width and a 20m length. Besides the 40 plots, 8 additional protection areas each with the same area as the plots were established. In each 180 m^2 plot (the so-called gross plot) a sub-plot (net plot) of 45 m^2 (4.5mx10m) was established for biomass sampling. The five locations differed mainly in precipitation, air temperature and management conditions concerning weed control and fertilization. The willow clones tested were Inger, Klara, Linnéa, Resolution, Stina, Terra Nova, Tora and Tordis(Fig. 1c) (for further details on genetic pedigree, see reference Larsen et al., 2014, referred bellow). Data of first harvest (available on Larsen et al,.2014) showed that the Tordis clone performed better along the five locations with an average yield on the first three year rotation of 6.7 tons. $ha^{-1}year^{-1}$, which was 36% higher than the average lower clone yield (Stina). In Foulum Tordis average yield in the first rotation (10.2 tons.$ha^{-1}year^{-1}$) was the highest comparatively to the other clones. The second clone with higher productivity in Foulum was Tora(9.6 tons.$ha^{-1}year^{-1}$). The yields in second rotation should be of course higher. The influence of site in biomass productivity on the first rotation was higher with Foulum ranking first (average 8.2 tons $ha^{-1}year^{-1}$ for all clones) vs. e.g. Odum with 4 tons $ha^{-1}year^{-1}$, a difference of about 50%. These differences were likely due to differences in management intensity and interactions between environmental factors. The yield results for the second three year rotation in 2016 were also obtained (unpublished data) and gave the same relevance to Tordis and Tora in Foulum. The results of the second rotation also showed a higher productivity in Foulum comparatively to Jyndevad. Also Toris and Tora were the clones with higher productivity in Jyndevad. In parallel, additional trials in Foulum showed advantages in using three year rotation cycles comparatively to one or two year rotation cycles. Also it was shown that Toris and Tora shoots in Foulum and Jyndevad showed the lower average amounts of K, Ca, Na and S and lower ash content, comparing with the other willow clones in the two sites.

In Foulum, we also visited the first poplar trials in Denmark implemented under a larger framework in three locations: Jyndevad, Skejby and Foulum. These trials were subjected to the same kind of management concerning weed control and fertilization. The main difference between these three sites was due to soil: coarse loamy soil in Jyndevad, loamy sand in Foulum and clayey loam in Skejby. The six poplar clones tested were Alasia AF8, Androscoggin, Hybryd 275, Max 1, Max 3, OP24 and as a reference a willow clone (Inger). See reference Laerk et al. 2015 bellow for further details on poplar genetic pedigree. Cuttings of 20 cm were used for plantation under a density of 12000 plants ha^{-1} in all sites and clones. Four plot replicates per clone were established with an individual plot area in Foulum of 180 m^2 (9m x 20m)(Fig. 1a). Max 1 and Max 3 were the clones with 25-28 $tonsha^{-1}$ (DM) in Foulum and Skejby. The clone AF8 was the one with lower productivity with 13-15 $tonsha^{-1}$ (DM) in Foulum and Skejby and 8 $tonsha^{-1}$(DM) in Jyndevad. Despite the higher productivity of poplar clone Max 3 its ash amount was relatively high, with known inconvenients to combustion. The unpublished data of second three year rotation for these poplar clones showed, as expected, an increased biomass yield with a higher biomass productivity of clone Max 3 and Foulum site. Clone AF8 maintained its lower productive performance due to high mortality. This lower productivity may be due to same factor related to harvesting, because in another visited trial in Foulum, with 5 year uncut stools, clone AF8 plants showed higher height and diameter growth.

1a) Poplar plots



1b) Willow plots



1c) Willow plots (clones)

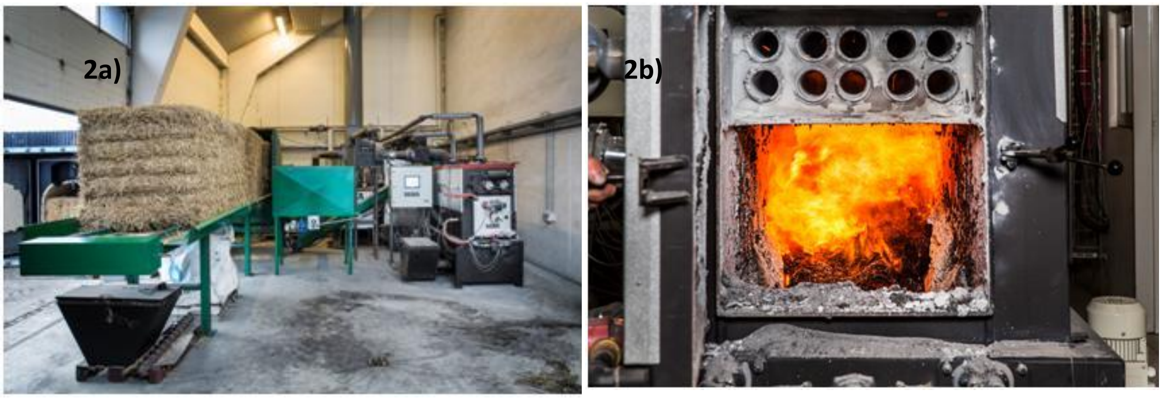
Foulum

Replicate					
1	Resolution	Tora	Inger 2y	Linnea	Inger
	Tordis	Klara	Inger 1y	Terra Nova	Stina
2	Stina	Linnea	Klara	Tordis	Inger 2y
	Inger	Terra Nova	Tora	Resolution	Inger 1y
3	Inger 1y	Resolution	Terra Nova	Inger	Tora
	Inger 2y	Tordis	Linnea	Stina	Klara
4	Tora	Stina	Tordis	Inger 1y	Terra Nova
	Klara	Inger	Resolution	Inger 2y	Linnea

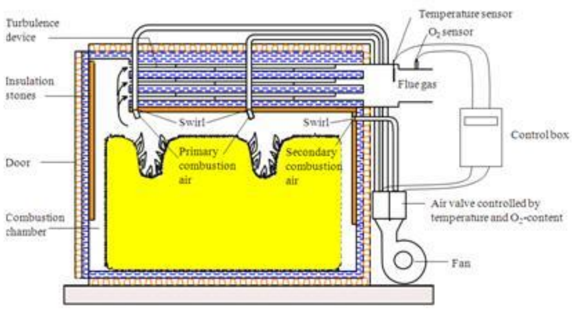
Fig. 1 – Diagrams for poplar and willow block randomized plots in Folum (1a)- poplar individual plot dimension 9x20m, 1b) - willow – individual plot dimension 9x20m, 1c) willow clones distribution under the same scheme as 1b;

In April 3 and April 4 we made an introductory visit to field trials of poplar and willow SRCs in the Foulum campus and also a visit to a batch pilot installation, optimized for wheat straw combustion. In these two days two trials of straw combustion were also performed under the valuable coordination of Dr. Erik Kristensen and technician Jens Kristensen members of the staff of Engineering Department of Aarhus University. It should be emphasized that a trial in combustion pilot scale of this kind of biomass, gives a good perspective of thermal conversion of woodchips from SRCs. This happens because the problematic of the relevance of scale of the operation can thereby be addressed for the planning and equating of thermal conversion of woody biomass falling in the scope of this COST Action.

The data analysis of these trials was made in April 5. In general, wheat straw has higher ash content than woody biomass (4% vs. 0.6-1.5%) and a HHV of the same order in magnitude. The alkali content is much higher in the herbaceous raw materials compared to woody and coal stuffs. Like other biomasses straw is carbon neutral, with a level of net zero carbon dioxide emissions usually considered. The basic conditions to assure good combustion with lower emissions are the atmospheric turbulence and temperature in the burning environment (boiler) and an enough time of residence, of the order of a few seconds, of hot combustion gases in the environment.



2c)



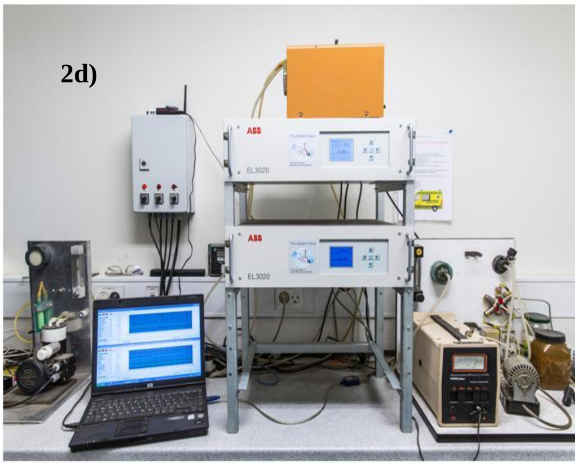


Fig. 2- Combustion equipment: 2a) feeding 500 Kg straw bale, 2b) burning, 2c) combustion chamber diagram and 2d) flue gas analysers.

The yield of combustion operation can be improved by supplying air in several stages (primary and secondary air). The supply of primary and secondary air is controlled with the equipments used to measure temperature and gases concentrations in flue gas.

The main equipments used in the two trials for straw burning and flue gas monitoring (Fig. 2) were i) Boiler(combustion chamber of 2.5 m^3) : Alcon, Model 1220 BA; ii) Temperature and energy monitoring: Kamstrup, Model Multical 402 (PT100 sensor); iii) CO analyzer: ABB, Model EL3020 Uras 26 and iv) CO_2 and O_2 analyzers: ABB, Model EL 3020 Magnos 26. The continuous data were stored on a CR1000 datalogger. Also laboratorial and pilot weighing machines were of trade mark Kern, Model ABJ 120 – 4NM and Scanvaegt Model SC500. The data are measured and averaged every minute with data acquisition equipment.

Two cubic samples of 200 Kg wheat straw with 13% moisture content and 3% ash content were used in both trials. The ash and moisture were determined gravimetrically and their values allowed obtaining an average HHV of 4.19 kWh/Kg of biomass according to the following expression:

$$HHV = (18.4-0.2(m_w+ash)/3.6$$

where m_w and ash are the moisture and ash contents (%) on a wet basis. This empirical equation was developed in the Foulum campus, and is valid also for woodchips, being thereby of big practical utility. Considering that the measured value of heat exchanged on water heating of 700 kWh, and an energy content of 200 Kg of wheat straw of about 840 kWh, it resulted an estimated average energetic yield of 83.3% for this pilot operation.

Essentially the evolution of straw biomass in the experiments was mainly dependent on the evolution of the geometry of the straw bale in the chamber with the proceeding of the combustion. The main parameter to be controlled was oxygen concentration in the flue gas, which is directly linked to flue gas temperature and oppositely associated with the carbon monoxide in this gas. The variation of flows in primary and secondary air, automatically triggered by the analyzers in flue gas assures these controls in gas concentrations and thereby in flue gas temperature. The total volume of flue gas for the Alcon boiler is about 500 m3 per hour. Specifically, the secondary air inflow is automatically triggered when oxygen concentration in flow gas is lower than 8%. The overall time evolution of combustion trial in April 3 is depicted in Fig.3. Fig.4 shows the evolution of that trial by parting the interval 9h54m-15h38m in three blocks. Indeed, we can establish a first stage of straw combustion, in April 3 in the period between 9h54m and 10h40m, (Fig.4a) wherein initial strong biomass combustion on the bale surface led to a drop in oxygen concentration in flue gas to a minimum of 0.5% and peaks of CO concentration and flue gas temperature of 11200 ppm and 198ºC, respectively. Thereby an additional supply of secondary air was imposed to stabilize the oxygen and carbon monoxide concentrations to about 7.5% and 400 ppm so that the average oxygen concentrations in this period (9h54m to 10h40m) were 8.1% and 2000 ppm respectively. The average flue gas temperature was also abated in this period to 140ºC. A second period occurred between 10h40m and 15h (Fig.4b) wherein the patterns of oxygen concentration and flow gas temperature were steady, with an average of 6.75%, of concentration and an average flue gas temperature of 153ºC. In this period the bulk of the straw bale was burned and a slight oscillatory pattern of oxygen concentration in flue gas and flue gas temperature can be due certainly to small changes in bale structure allowing to slight differential patterns of flame distribution, which were of course monitored to gas analyzers, trigging thereby minor changes in supply in primary and secondary air. Finally, when the upper-half of the straw bale was burned, a third stage on the combustion could be evaluated from 15h till the end of the combustion process at 15h38m (Fig.4c). At this later stage the access of primary air was of maximum, due the emptier space, while the feeding of secondary air was closed. The main features registered in this period were the peaking of flue gas temperature to temperatures as high as 226ºC, and of the oxygen concentration as well to levels above 10%, excessive because the straw was overly incinerated. A collapse of the bale induced a partial smothering of the adjacent atmosphere with an episodic increase of CO emissions up to 3000 ppm. The combustion was assumed as finished when the oxygen content in the flue gas exceeded 18%. In the April 3 trial an isokinetic sampling of particle emissions in the flue gas in six periods on the trial: 1- 9h57 till 10h45, 2- 10h58 till 11h50, 3- 11h58m till 12h50, 4- 12h57 till 13h50, 5- 13h58 till 14h52 and 6- 14h57 till 15h 38m. The average volume of gas sampled was 0,403 m^3 and the average emission of particles was 516 mg per nm^3, well above the threshold of 60 mg per nm^3 required by environmental protection standards for batch fired straw boilers. The threshold value will be applied from January 2018 onwards.

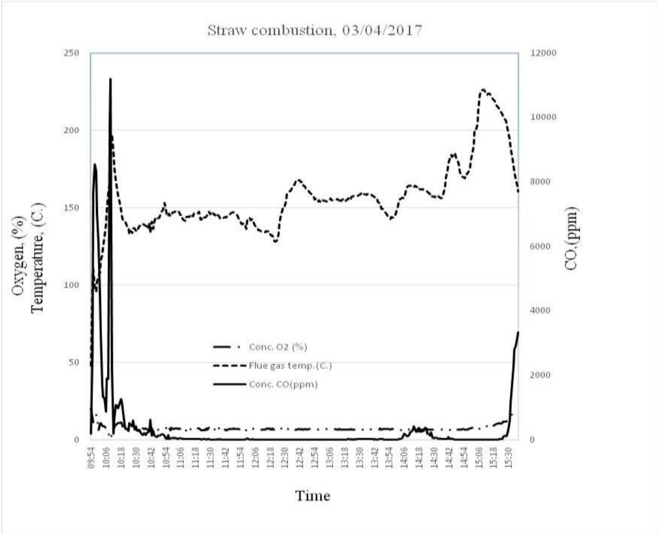
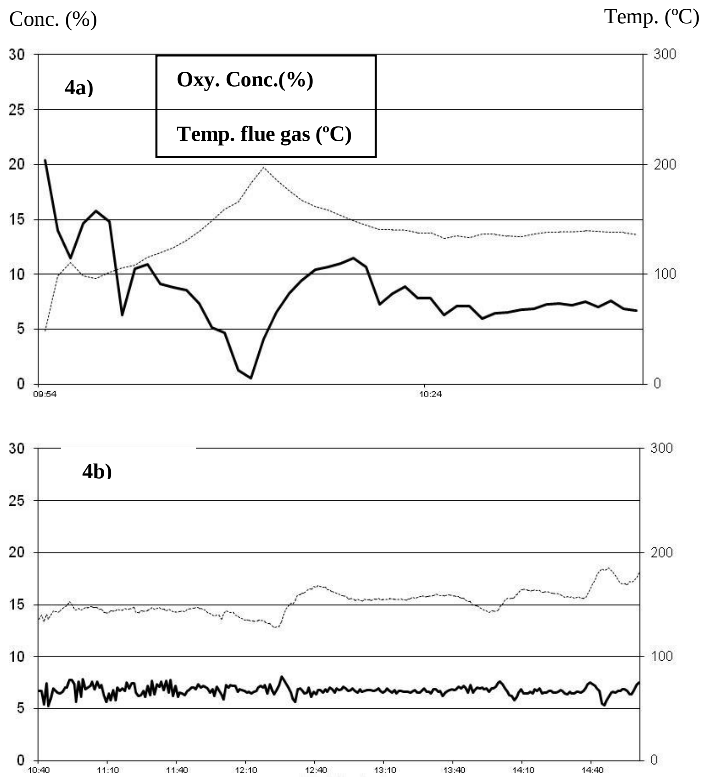


Fig. 3 - Evolution of straw combustion in 3 April trial concerning to the time variation of 3 variables.



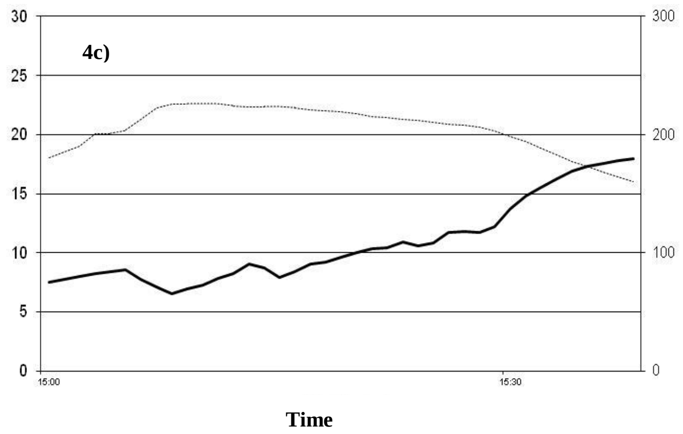


Fig.4– Evolution of combustion process in April 3. Figs.4a), 4b) and 4c), concern to time periods 9h54m-10h40m, 10h40m-15h and 15h-15h38m, respectively.

A similar overall pattern of combustion (not shown) was registered for the combustion trial of April 4 occurring during about 5 hours. The heat released by the combustion was used in water heating from a quasi steady temperature of 64ºC to a steady temperature of 92ºC. The average flow of water was $12.12m^3h^{-1}$.

In a summary, this STSM in Foulum campus of Aarhus University was intended to obtain a scope of how a prestigious institution can implement an integrated vision of woody biomass production and conversion on a pilot scale campus. The plot trials of 8 clones of willow and 6 clones of poplar SRC were designed, under a randomized block design, to test how the interactions among environmental, management and genetic factors affect biomass yield. The poplar trial was the first to be installed in Denmark.

This mission allowed thereby i) a contact with experimental design for different clones of poplar and willow SRCs in field with replications and with the introduction of environmental and management variables, and on specifics of data treatment as well; ii) an evaluation of the importance of willow SRC in Denmark; iii) an evaluation in the field trials of the relevance different rotation cycles on biomass yield; iv) the continuous monitoring of biomass combustion dynamics concerning variables of the flow gas on a pilot scale batch boiler of a 200 kg biomass sample; v) a continuous feedback processes for controlling the turbulence and air feeding on the boiler and vi) evaluating energy and mass balances and particle emissions of the combustion process. We cannot finish this report without express our greetings to colleagues Poul Laerke, Uffe Jorgensen, Erik Kristensen and Jens Kristensen for the valuable support given for this work.

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