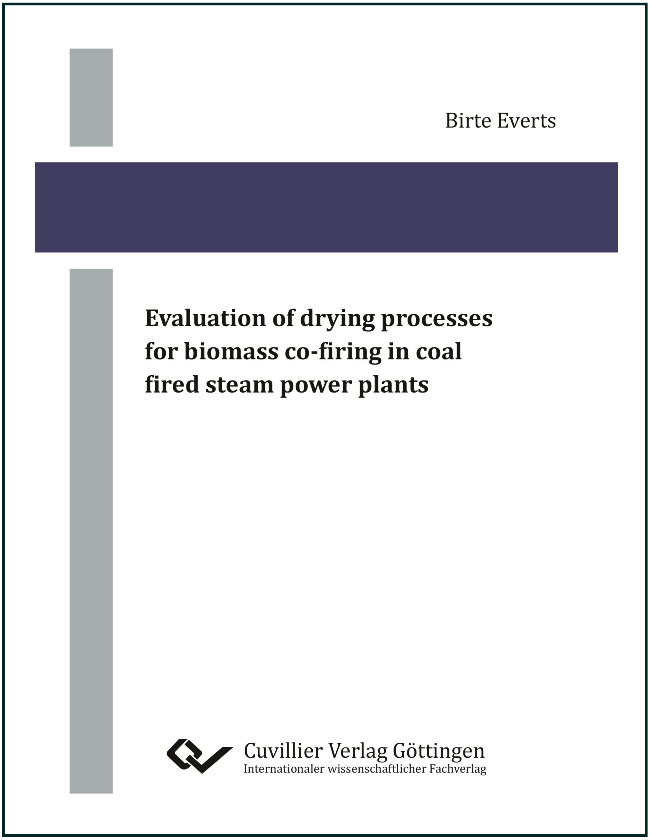
Birte Everts (Autor)

Evaluation of drying processes for biomass co-firing in coal fired steam power plants



https://cuvillier.de/de/shop/publications/7434

1 INTRODUCTION

A higher share of renewable energies in power generation is being striven for in many countries, especially in Europe. More sustainable forms of energy utilisation are desired in order to meet targets for greenhouse gas reduction designed to limit climate change.

In Germany, wind and solar energy are the main resources of renewable power generation [1]. However, one major disadvantage of these weather-dependent forms of power generation, compared to power generation from fossil fuels, is the impossibility of adjusting their power generation in response to variable needs. Using biomass as a fuel for a conventional steam power plant can provide adjustable power generation and simultaneously reduce greenhouse gas emissions. The CO_2 emissions caused by burning biomass are assumed to be balanced by the CO_2 absorbed in the growing process. Therefore, burning biomass is counted as carbon neutral.

Biomass in general includes all living or dead organic matter and its residues and products, unaltered or transformed by technical processes [2]. Of course, not all types of biomass are suitable for power generation, but solid biomasses with a high carbon content, such as wood or straw, can be used as fuel.

When co-firing biomass with coal, some of the fossil fuel in a conventional steam power plant is substituted by a renewable fuel.

1.1 Background

Today in Germany, power generation from solid biofuels is subsidised only for the use of 100 % biomass and up to 20 MW of electrical power generation [3]. As a result, there are many small, decentralised facilities dedicated to solely firing biomass. Co-firing biomass with coal in large-scale coal-fired steam power plants is not subsidised in Germany, even though this practice would have several benefits. Firstly, already existing infrastructure could be used. The construction of a new power plant and the necessary grid connection would not be required, which is economic and resource-saving at the same time. Secondly, large coal power plants are mostly very well designed and usually operate with far higher process efficiencies than small biomass-only facilities are able to achieve. The same amount of biomass energy can be converted into a larger amount of electricity through co-firing in a large-scale coal power plant compared to the use of a small biomass-only power plant.

Co-firing activities are currently carried out in the UK, the Netherlands and most Scandinavian countries. The most commonly used fuel for co-firing in these countries is white wood pellets. It is current practice to import these from North America, but the sustainability and carbon neutrality of power generation based on fuels imported from overseas is questionable. Therefore, the focus should be on using locally available biomasses for co-firing.

Short-rotation plantations offer the possibility of providing large amounts of woody biomass. Fast-growing species, such as poplar or willow, can be harvested in perennial cycles, and are generally high-rank biomass fuels. If cultivated in the vicinity of the power plant, the overall sustainability of co-firing could clearly be improved.

Probably the greatest obstacle in using wood chips from short-rotation plantations for co-firing in coal power plants is the high moisture content of freshly harvested wood, which is around 50 %. To upgrade the biomass fuel, and in doing so limit the problems that might arise from co-firing, drying the wood chips prior to co-firing is essential.

1.2 Aim and scope

This thesis aims to identify and analyse the effects of biomass co-firing in coal-fired steam power plants at high rates of up to 50 %, based on fuel heat input. Each power plant is usually designed for a certain fuel. If, like in co-firing, a fuel with different properties is fired, operation cannot be expected to match design operation. The limitations and impairments of co-firing coal with wood chips on the power generation process in a large-scale steam power plant will be highlighted below and, if possible, quantified.

As the poplar wood chips need to be dried prior to co-firing, several drying technologies will be considered in order to identify a suitable drying process. Large-scale steam power plants require a very high fuel heat input, so an efficient method for drying significant mass flows of wood chips would be required. The influence of several process parameters on each drying process's energy demand will be analysed. Also, the possibilities and limitations of using heat sources from the power generation process for drying will be investigated.

Several scenarios for drying and power generation will be developed and analysed in order to identify the most favourable way of drying poplar wood chips for co-firing in a coal-fired steam power plant. Also, the effects on the power generation process of integrating drying processes into the water-steam cycle or the flue gas track will be considered. Again, the limitations and impairments of co-firing biomass with coal will be analysed and quantified. To complete the scenario analyses, CO_2 emissions caused by transporting the wood chips from a short-rotation plantation to the power plant will be included.

1.3 Methodology

All the thermal processes analysed in this thesis are modelled and simulated using EBSILON®*Professional*. This modelling tool was developed for designing and analysing thermodynamic cycle processes and provides a wide range of process compounds, as well as the possibility of creating additional compounds. The simulation results of all the analysed processes are the main resource for this study's conclusions.

Chapter 2 summarises current activities and experiences in biomass co-firing with coal. Different biomasses are compared with regard to their fuel characteristics. Also, the possible effects resulting from fuel composition while co-firing are considered. Additionally, several methods of fuel supply are introduced and evaluated.

Chapter 3 outlines the technical possibilities for drying large mass flows of poplar wood chips matching the requirements of co-firing with coal. Two different drying technologies, indirect steam-tube dryers and direct rotary dryers, are identified as suitable and their technical details and process characteristics are presented.

Chapter 4 describes the model developments of the boiler, the power generation process and the dryers. The power plant considered is modelled based on information provided by a German utility. The drying processes are modelled based on information gained through literature research and communication with dryer manufacturing companies.

Chapter 5 evaluates the effects of direct biomass co-firing on the power generation process. In the first stage, changes in heat transfer and the process parameters of the boiler are analysed. Afterwards, further effects on the overall process are demonstrated and interpreted.

Chapter 6 develops three scenarios for drying and co-firing poplar wood chips in large-scale steam power plants. An indirect steam-tube dryer would need to be integrated into the power plant's water-steam cycle in order to be supplied with the necessary drying heat. A flue-gas-heated direct rotary dryer could function in a stand-alone version or be integrated into the power plant's flue-gas track. The heat demand of a stand-alone rotary dryer could be covered by burning biomass or fossil fuels.

The technical challenges in realising each scenario are discussed and, if technically feasible, the most favourable drying scenario would be the one with the lowest total resulting CO_2 emissions and highest overall energy utilisation efficiency. The total resulting CO_2 emissions are calculated by adding together the CO_2 emissions caused by power generation, drying and fuel transportation. To determine the overall energy utilisation efficiency, the additional energy input for drying in the non-integrated scenarios is included in an overall energy balance.

2 Co-firing biomass with coal

There are multiple ways to realise power generation from biomasses. One of them is the co-firing of biomass with coal, which itself can be carried out in different ways. However, in this thesis, only the co-firing of solid biomass in pulverized hard-coal-fired large-scale steam power plants will be considered.

Three main concepts for biomass co-firing are generally distinguished [4]:

- direct co-firing
- indirect co-firing
- parallel co-firing

Technically, direct co-firing is the simplest approach. No significant modifications of the existing power plant are required for its realisation. The biomass fuel is fed directly into the coal mass flow or ground separately. In the first case, biomass is co-milled in vertical spindle mills. In the second case, the pulverized biomass can be injected into the pulverised coal mass flow upstream of the burners, although combustion by dedicated biomass burners is also possible. This concept is most commonly applied when co-firing biomass with coal.

For indirect co-firing, a fuel pre-treatment process is installed at the power plant site, which can also be integrated into the power generation process. This method of biomass co-firing requires greater investment and the operation of an additional complex process. However, it also allows the use of a broader range of biomasses, as the fuel properties can be adjusted to the power plant's requirements.

Parallel co-firing of biomass with coal requires a separate boiler for biomass combustion, since only the water-steam cycles are connected, with the biomass and the coal being combusted separately. Out of all three concepts, this requires the greatest number of necessary modifications to the existing power plant. However, it also enables the use of a wide variety of biomass fuels, as the biomass boiler is specially designed for biomass combustion only. This can help avoid the problems that typically occur in co-firing biomass with coal.

2.1 Current Co-firing activities in power generation

Currently, biomass co-firing with coal is carried out in a small number of power plants in Europe. Along with many short term trials [5], [6], [7], [8], [9], [10], incentives have led to permanent co-firing activities, or even full conversion to biomass-only firing in countries like Denmark, the Netherlands and the UK. The co-firing of biomass with coal in large-scale steam power plants first started at the beginning of the new millennium.

Using biomass fuels for combined heat and power generation has a significantly longer tradition and is widely used in Austria and in all Scandinavian countries [11], [12], [13], [14]. Their local wood industry provides large amounts of wood residue that is often used in small-scale CHP plants.

The present thesis will only consider biomass co-firing in pulverised coal-fired, large-scale steam power plants. Table 1 lists a selection of such power plants currently co-firing biomass with coal in Europe.

Recently, the city of Copenhagen declared its intention of becoming the world's first capital city with a carbon neutral heat and electricity supply, by 2025 [15]. As a result, several units of the combined heat and power plants in Amager and Avedøre have already been fully converted to biomass combustion, and the conversion of further units is planned for future years [16]. Other power plants in Denmark use agricultural residue straw for co-firing. Studstrup power station, with a co-firing rate of 20 % based on fuel heat input, is just one example.

In the Netherlands, subsidy programmes have encouraged co-firing activities in various power plants. Co-firing rates do not exceed 10 % in most cases. The chosen biomass fuel is, once again, wood pellets. This is also the case for the fully converted Unit 4 at Rodenhuize power station in Belgium.

Several large facilities in the UK have been fully converted to power generation from biomass. In Drax power station, the third unit has been fired 100 % by wood pellets since 2015. Together with the biomass co-firing activities at Ferrybridge and other power plants, more than 600 MW_{el} of carbon neutral electricity is currently generated in the UK.

Table 1: Selection of large-scale European coal power plants with current biomass co-firing activities

Power plant		Biomass	Co-firing rate	References
Amager (DK)				
	Unit 1	Wood pellets	100 %	[17], [16]
	Unit 2	Straw pellets	100 %	
Avedøre (DK)				
	Unit 1 Unit 2	Wood pellets	100 %	[18],[19], [20]
Studstrup (DK)				
	Unit 1	Straw	20 %	[21], [4], [22]
	Unit 4	Straw	20 %	
Amer (NL)				
	Unit 9	Wood pellets	27 %	[23], [24]
	Unit 8	Wood pellets	10-12 %	
Gelderland (NL)				
	Unit 13	Wood, waste wood	5-8 %	[24]
Maasvlakte (NL)				
		Biomass pellets	6 %	[24]
Borselle (NL)				
		Kernels, paper sludge, shells, fibres	10-15 %	[24], [22]
Rodenhuize (B)				
	Unit 4	Wood pellets	100 %	[25]
Drax (UK)				
	Unit 1 Unit 2 Unit 3	Wood pellets	100 %	[18],[25]
Ferrybridge (UK)				
	Unit 1 Unit 2	Wood pellets, palm kernels, olive stones, olive cake	20 %	[18]

2.2 Biomass fuel characteristics and resulting effects in the combustion system

Biomasses currently used as fuel for energy production are in most cases woody or herbaceous biomasses, either residues from various sources or energy plants cultivated for the purpose of energy production. Fast-growing woods like poplar or willow, for example, can be cultivated in short-rotation plantations. Spruce, on the other hand, is one of the most common tree species in the wood industry in Europe and North America. Another solid biomass fuel is straw, which represents a herbaceous biomass and is available as an agricultural residue.

Regarding their fuel characteristics, these biomass fuels can deviate significantly from fossil fuels. Typical elemental compositions for the dry matter of hard coal, lignite, poplar, willow and straw are listed in Table 2 [2]. Fossil fuels and biomass fuels differ most obviously in their oxygen content. While typical hard coals are characterised by an oxygen content of around 10 %, typical biomass fuels usually have an oxygen content of more than 40 %. As a result, the carbon content in biomasses is clearly lower.

Table 2: Composition of various biomass fuels and coals [2]

Fuel type	C	H	O	N	S	Cl	Ash
			in wt.-% of dry matter				
Hard coal	72.5	5.6	11.1	1.30	0.94	0.130	8.430
Lignite	65.9	4.9	23.0	0.70	0.39	0.100	5.010
Poplar	47.5	6.2	44.1	0.42	0.031	0.004	1.745
Willow	47.1	6.1	44.3	0.54	0.045	0.004	1.911
Spruce	49.8	6.3	43.2	0.13	0.015	0.005	0.550
Straw	45.6	5.8	42.4	0.48	0.082	0.190	5.448

The fuels' heating values depend on their elemental composition and moisture content. In this paper, the following equation (Eq. 2.1) from Boie [26], [27] is used to calculate the higher heating value HHV_{db} on dry basis:

$$HHV_{\mathrm{db}} = \big(151.2 \cdot \gamma_{\mathrm{C,db}} + 499.77 \cdot \gamma_{\mathrm{H,db}} - 47.7 \cdot \gamma_{\mathrm{O,db}} + 45 \cdot \gamma_{\mathrm{S,db}} - 27 \cdot \tag{2.1}$$

$\gamma_{\mathrm{N,db}} - 189) \cdot 2326 \quad \text{in kJ/kg}.$

With $\gamma_{\mathrm{C,db}}$, $\gamma_{\mathrm{H,db}}$, $\gamma_{\mathrm{O,db}}$, $\gamma_{\mathrm{S,db}}$ and $\gamma_{\mathrm{N,db}}$ being the mass shares of carbon, hydrogen, oxygen, sulphur and nitrogen on dry basis of the biomass fuel.

The higher heating value HHV_{db} can be converted into the lower heating value on dry basis LHV_{db} with Eq. 2.2 by subtracting the evaporation enthalpy of the water created by combusting the fuel hydrogen:

$$LHV_{\mathrm{db}} = HHV_{\mathrm{db}} - 2442 \cdot \left(8.936 \cdot \gamma_{\mathrm{H,db}}\right) \quad \text{in kJ/kg}. \tag{2.2}$$

The results for the lower heating values on dry basis for the biomasses poplar, willow, spruce and straw are shown in Table 3. Due to its comparatively high carbon content, the LHV_{db} of spruce is higher than those of the other fuels.

Table 3: Lower heating values of biomass fuels

	Poplar	Willow	Spruce	Straw
$\boldsymbol{LHV_{\mathrm{db}}}$ **(MJ/kg)**	17.20	16.94	18.22	16.35

With Eq. 2.3, the lower heating value of biofuels on wet basis LHV_{wet} can be calculated based on LHV_{db} and the fuel moisture content $\gamma_{\mathrm{H_2O}}$:

$$LHV_{\mathrm{wet}} = LHV_{\mathrm{db}} \cdot \left(1 - \gamma_{\mathrm{H_2O}}\right) - 2.442 \cdot \gamma_{\mathrm{H_2O}} \quad \text{in kJ/kg}. \tag{2.3}$$

The fuel moisture content has a substantial influence on the lower heating value LHV_{wet} of a fuel. Figure 1 shows the dependence of the lower heating values LHV_{wet} of spruce, poplar, willow and straw on fuel moisture content. Starting from lower heating values on dry basis of around 17 000 kJ/kg, the fuel energy content drops to lower heating values of around 9 000 kJ/kg for a fuel moisture content of 50 %.

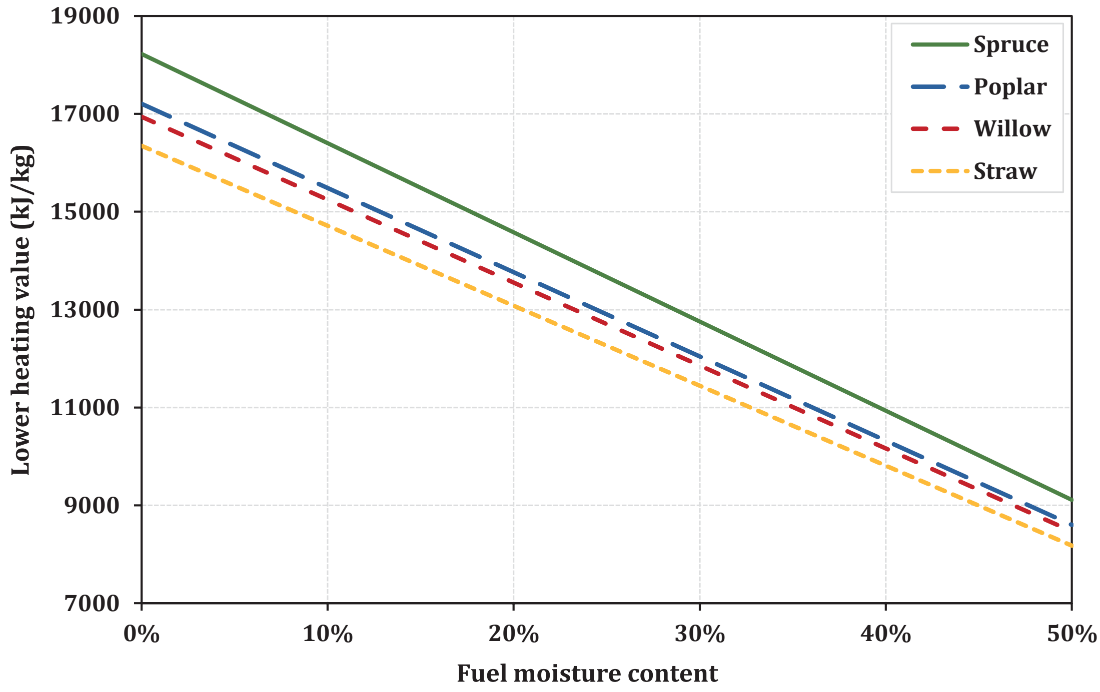


Figure 1: Lower heating values of biomass fuels for varying fuel moisture content

Table 2 also shows that woody and herbaceous biomass fuels generally have a lower ash content than hard coal. Nonetheless, the biomass ash might be problematic in co-firing, as the composition of biomass ash deviates from that of coal. VASSILIEV *et al.* [28], [29] analysed the composition of several biomass ashes, including beech wood, corn cobs, microalgae, plum pits, rice husks, switchgrass, sunflower shells and walnut shells. Table 4 shows the resulting mean value for each ash component, as well as the range of analysis results. Alongside biomasses, several hard coal ashes were also analysed. To gain a better picture of typical ash compositions, the results of poplar [30], eucalyptus and a second hard coal ash [31] are included in Table 4. Due to differing analysis methods, different elements are identified for ash composition.

The results show a very wide range in biomass ash composition, which underlines one of the most important characteristics of biomass fuels. Even within one biomass species, the fuel and ash composition can vary significantly. Coal ash composition can also vary. However, general differences between the ashes of woody biomass (here poplar and eucalyptus) and coal ashes can be specified. Coal ashes are richer in silicon and aluminium oxides, whereas most biomass ashes are richer in potassium and calcium oxides.

Table 4: Composition of coal and biomass ashes

	Coal ash [28] (wt.% db)	Biomass ash [28] (wt.% db)	Poplar ash [30] (wt.% db)	Eucalyptus ash [31] (wt.% db)	Coal ash [31] (wt.% db)
SiO_2	54.06 (32.04-68.35)	29.14 (0.02-94.48)	14.0	26.50	44.80
CaO	6.57 (0.43-27.78)	25.99 (0.97-83.46)	34.0	21.80	23.10
K_2O	1.60 (0.29-4.15)	19.40 (2.19-63.90)	10.0	10.25	3.57
P_2O_5	0.50 (0.10-1.70)	5.92 (0.54-40.94)	3.0	2.88	1.13
Al_2O_3	23.18 (11.32-35.23)	4.49 (0.10-15.12)	1.7	7.60	6.21
MgO	1.83 (0.31-3.98)	5.60 (0.19-16.21)	4.8	5.88	2.55
Fe_2O_3	6.85 (0.79-16.44)	3.41 (0.22-36.27)	0.6	5.13	4.50
SO_3	3.54 (0.27-14.42)	3.27 (0.01-14.74)	-	2.53	3.53
Na_2O	0.82 (0.09-2.90)	2.54 (0.09-29.82)	0.9	2.52	1.52
TiO_2	1.05 (0.62-1.61)	0.24 (0.01-2.02)	-	0.33	4.07
BaO	-	-	-	0.22	0.49
Mn_3O_4	-	-	-	2.03	0.57

The following problems are commonly associated with biomass combustion, mainly occurring due to its lower ash-fusion temperature, caused by a high share of alkali components [4], [10]: