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A modelling approach for the assessment of an air-dryer economic feasibility for small-scale biomass steam boilers

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ABSTRACT

Fuel drying is an energetically and economically expensive pretreatment process, which may not be worth the investment in the case of small-scale generation plants. This paper presents an investigation on the air dryer feasibility to enhance the operation of biomass steam boiler. In the proposed approach, the external drying technology using preheated air and the biomass steam production system is modelled in terms of energy and an economical analysis. A focus is given to the system size influence on the dryer economic suitability: the smallest size of the biomass combustion system for which fuel drying is a suitable solution, from the economic point of view, is computed. In the computations, the heat used for drying is assumed to be part of the cost for operating the dryer and the thermal balance of the system is assumed to be previously verified. According to the model results, if the steam production plant operational time is above 8000 h/y, wood chips drying is feasible if the system size is larger than 1.78 t_{daf}/h of fuel processed.

1. Introduction

1.1. Technical context

The biomass feedstock for energy production often contains a high moisture fraction: freshly cut biomass can include up to 65%$_{w,wb.}$ (percentage on weight, on wet fuel basis) moisture when harvested, depending on the type of biomass and the environmental conditions.

External (or surface) moisture is the moisture fraction above the equilibrium moisture content and it generally resides outside the biomass cell walls. Inherent moisture, on the other hand, is absorbed within the cell walls. When the walls are completely saturated, the biomass is said to have reached the fibre saturation point, or equilibrium moisture [1]. The fibre saturation point increases with the relative humidity of external air and lower temperatures (Fig. 1) [2]. In wet and cold climates, the inherent fuel moisture might be as high as 30%$_{w,wb.}$ [2]. As a consequence, open air drying is not effective. Despite unforeseeable climate conditions (and logistical problems) leaving wet biomass outdoors can have at times a positive effect concerning moisture [3]. Biomass materials are also hygroscopic; even dried and stored, they can still absorb moisture from the atmosphere, until the equilibrium moisture content is reached [3,4].

In most cases active drying is a necessary pre-treatment process related to the technologies of thermal conversion of biomass: a high moisture content decreases the efficiency of the energy conversion, since the moisture must be first evaporated. To guarantee combustion quality, some industrial boiler technologies require the minimum low heating value (LHV) of biomass fuel to be above 15 MJ/kg$_{wb.}$ [3]. Moreover, the auto-thermal and self-supporting combustion limit, for most biomass fuels, is around 65%$_{w,wb.}$ of water content [5,6].

If the fuel moisture fraction is below the auto-thermal self-supporting combustion limit, drying is not necessary for combustion (in grate furnaces), but results in demonstrated benefits [1,3,4,7], such as:

- Increased and homogenised fuel LHV, with a decrease in the requirements for the combustion air pre-heating and process control.
- Increased flame temperature, hence a potential increase in the steam production in existing facilities. According to Van Loo [3], if the biomass fuel is dried from a moisture content of 50%$_{w,wb.}$ to 30%$_{w,wb.}$, the boiler thermal efficiency can potentially be improved by 8–10%. A lower air excess ratio may also be used if a more complete combustion is reached thanks to the higher temperature.
- In existing combustion facilities, a decrease in the amount of flue gases passing through the boiler (smaller emissions control equipment) and lower product gas velocities (potential decreased erosion). In case of a new plant design, smaller heat exchange surfaces are needed (decreased boiler dimensions).

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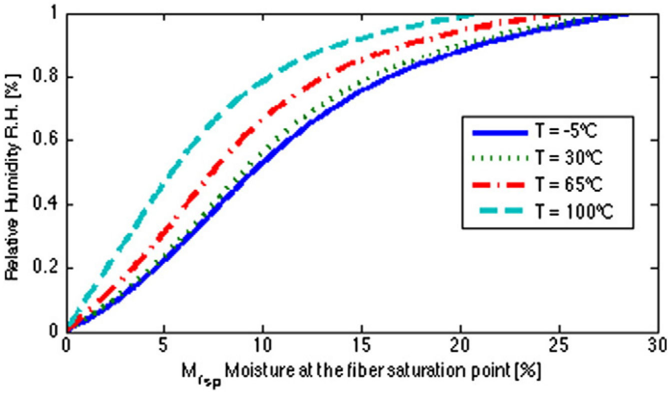

Fig. 1. Equilibrium moisture content of wood as a function of relative humidity and temperature (moisture at the finer saturation point), computed using the correlations proposed in the Wood Handbook [2].

- In case of long term storage, reduced risk of biological contamination problems.

These potential advantages are counterbalanced by numerous issues [4,5,8–10]:

- Dryers have a relatively high investment cost, which largely impacts small-scale plants. Globally, though the boiler thermal efficiency increases, the costs savings remain moderate [3]. Moreover, drying is an energy intensive operation.
- Explosions could occur and fires might arise if fuel ignition is reached during drying operation. Fire protection systems are necessary, increasing the system investment costs.
- The dryer effluents have to be treated as exhaust gases or as wastewater discharges.
- Burning very dry biomass (e.g. <10$\%_{w,wb.}$) may increase the *CO* and the total particulate emissions [11]. Furthermore, the boiler operational temperatures, if increased, can approach the fusion temperature of some of the fuel ash constituents, increasing the slagging risk.
- If the boiler is designed for processing dry fuel and the dryer fails, the boiler becomes undersized for burning wet fuel. A backup low-moisture fuel may be needed.
- Wet fuels can be utilized in grate combustion boilers, by increasing the combustion air preheating (e.g. 300–350 °C) or by means of proper Flue Gas Recirculation (FGR). However, grates capable of handling high combustion air temperatures, advanced air preheaters and excellent refractories are necessary [4].

Additionally, the use of different drying media determines benefits and concerns (Table 1). Looking at the dryer energy efficiency and energy integration in the plant, flue gas drying and steam drying are to be preferred. However, with respect to air drying, both technologies might have lower capacity and control characteristics.

The use of low-enthalpy flue gas to dry the fuel is usually the less expensive solution, but fuel ignition is a risk in presence of sufficient oxygen and high temperature [12,14]. Air drying is the most flexible solution and the process efficiency can be improved using multistage drying [15]. Steam drying is sensitive to the material size and size uniformity and, in general, despite the low heat specific consumption (kJ per kg of water evaporated), is more expensive. In case of superheated steam dryers, the latent heat of vaporization and the water is easy to recover and treat because the water vapour is not diluted with air [14]. Finally, the drying technology can be chosen (e.g. rotary dryers, belt dyers, flash dryers), taking into account that each technology has specific technical limits (e.g. the operating temperature) [14,16–19].

In conclusion, the choice of drying or not the fuel for power production is not a trivial task. In case of larger biomass combustion units (above 30 MW_{th}) it has been experienced that it is worth paying the investment for a feedstock dryer to improve the steam production efficiency. A moisture content of 35$\%_{w,wb.}$ is a trade-off between the enhanced combustion performance and the increased capital cost [20]. The trade-off between the dryer investment and the operating costs on one side, and the enhanced boiler efficiency on the other side, in case of small-scale distributed combustion systems is seldom explicitly studied in the literature.

Table 1
Multi-criteria analysis for different drying media available [8,11,12]. Configurations where different drying media are coupled are also commercially available.

	Air	Steam	Flue gases
Energy efficiency and heat integration	−	+	+
Dryer effluents[a]	−	+	+
Fire and explosion risks	−	+	−
Fuel size flexibility	+	−	+
Control and capacity	+	−	−

[a] Dryer emissions depend also on the biomass type [13].

1.2. Literature review

Brammer and Bridgwater [21] focused on the influence of feedstock drying on systems coupling a small-scale biomass gasifier and an internal combustion engine. The minimum cost of electricity produced was determined incorporating a rotary dryer with a burner, drying from an initial moisture content of 50$\%_{w,db.}$ (percentage on weight, dry basis) to a final moisture content of 10$\%_{w,db.}$. The highest overall energy efficiency was obtained with drying to a final moisture content of 35$\%_{w,db.}$.

Gebreegziabher et al.'s [9] approach was to maximize the annual profit of the operation of the dryer for biomass combustion, without modelling the steam plant. The optimum solution indicated that the dryer subsystem is profitable with the moisture level of the dried wood at 17$\%_{w,wb.}$. Moreover, when the size of the wood chips becomes too large, the drying time is too long, thus significantly increasing the dryer size and energy cost.

Ho Ting Luk et al. [10] investigated how drying affects the overall energy efficiency of a 12.5 MW biomass power plant that burns Empty Fruit Bunch (EFB), a feedstock with 60$\%_{w,wb.}$ moisture, to support proper heat integration between the dryer and the power plant. In their study, two types of dryers (which have different operating temperatures), a Hot Air Dryer and a Superheated Steam Dryer, are proposed for the drying process. With proper heat integration, the overall efficiency of the production plant could be improved by about 5% when compared to process without drying. The economical aspects of drying were not investigated.

In [13], H. Li et al. presented the results of a model of a belt conveyor drying system for pine wood chips at 60$\%_{w,wb.}$ inlet moisture content, with flue gas and steam as drying agents, that could provide dried fuel to a 40 MW plant. While using flue gases as the heat source for drying, the dryer capital cost computed was about €2.5 million; while using superheated steam, the capital cost was about €3 million, because of the higher quality steel in the equipment. The evaluation of the dryer profitability was performed defining a fuel-selling price, after the dryer, without modelling the successive energy conversion. At a dried fuel selling price of 14 €/MWh, 3–4 years of operation was expected to give a return on the initial dryer investment.

H. Holmberg and P. Ahtila in [22,23] have compared the exergy efficiencies and the drying costs (capital and operational) of two types of drying systems: single-stage drying with partial recycle of spent air, and multi-stage drying. According to the results, the irreversibility production depends to a considerable extent on the heat source and the drying system. The single-stage drying is usually more economic when the amortisation time is short. However, the competitiveness of multi-stage drying improves as the amortisation time becomes

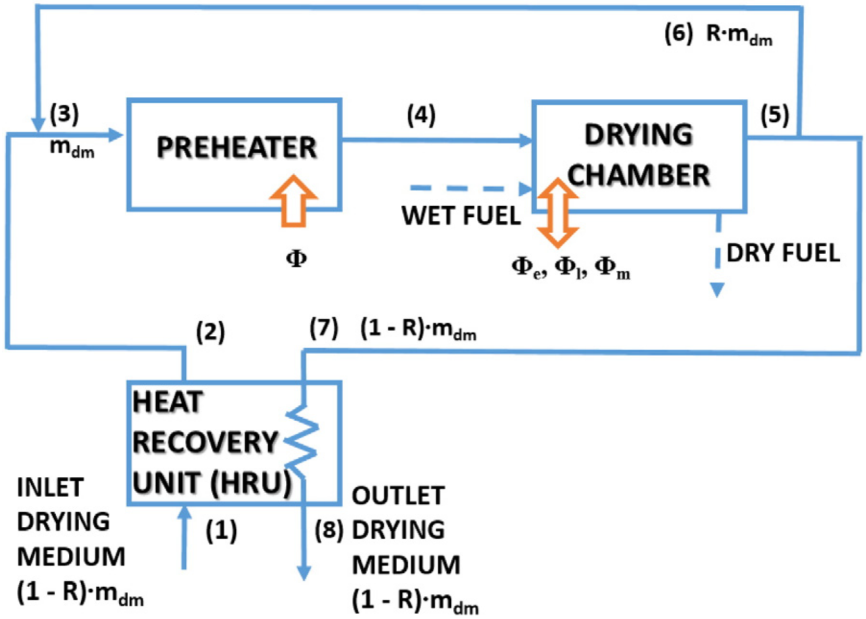

Fig. 2. Single stage air drying system with partial recycling of exhaust (dm: drying medium, R: recirculation factor). Adapted from [15].

longer. In his PhD Thesis [15], H. Holmberg presents the heat specific consumption and specific irreversibility computations for multi-stage air drying with partial recycle of spent air and a Heat Recovery Unit. The optimally designed dryer consists of two drying stages, drying the fuel to the final moisture content of $30\%_{w,db}$.

1.3. Objective of the study

To contribute to the analyses developed in the previous investigations, this paper presents a study on the dryer economic feasibility with a focus on small-scale biomass combustion systems. The plant size range explored is 1–6 t_{daf}/h (dry and ash free) woody fuel at the inlet of the dryer and combustion boiler (<30 MW_{th}). A dryer using preheated air and the biomass steam production system are modelled in terms of energy and an economical analysis. The choice to model an air dryer is related to its flexibility, to the medium availability, and to the possibility to use both an external or internal thermal source to produce the medium at the desired thermodynamic condition. To assess the dryer suitability, the additional steam produced in the boiler, thanks to the use of dried fuel, is evaluated in economic terms and compared with the estimated total dryer costs. In the computations, the heat used for drying is assumed to be a cost for operating the dryer. The thermal integration of the dryer and the steam production system is not investigated. The energy balance should be verified, in a previous step, depending on the configuration, on a case-by-case basis. Given the parameters, the key finding of the modelling approach is the smallest biomass combustion system for which an air-dryer would be economically feasible.

Table 2
Model variables and values for the drying sub-model for the base case analysis.

Input parameters		
Medium inlet T_1 [a]	[°C]	15
Medium inlet p_1 [a]	[kPa]	101.32
Flow r. humidity RH_1	[−]	0.50
Flow r. humidity RH_5	[−]	1.00
Medium p. losses Δp	[kPa]	1.50
Medium velocity v	[m/s]	0.65
Recirculation factor R [a]	[−]	0.30
Fuel dry mass flow $m_{w,1}$ [a]	[kg/s]	1.0
Fuel moisture (in) $M_{w,1}$	[% w,wb.]	60
Hot source $q_{h,s} = \Phi/m_{dm}$ [a]	[$kJ/kg_{dry,air}$]	130
$T_{hot-source}$	[°C]	150
Heat hx. thermal losses l	[%]	2
Dryer th. loss Φ_l	[%]	10
Power consumpt. Φ_{m+e}	[kW]	2.0
Heat hx. factors U_i	[$W/m^2/K$]	10
Fuel T. dryer step $T_{w,2}$	[°C]	ΔT = 5
Output parameters		
Dryer area A_d	[m^2]	
HRU area A_{HRU}	[m^2]	
Pre-heater area A_{hx}	[m^2]	
$C_{INV,dryer}$	[€]	
Dryer heat consumption	[kJ/kg_{H_2O}]	
Fuel moisture (out) $M_{w,2}$	[% w,wb.]	
Drying medium m_{dm}	[m^3/s]	

[a] Values are varied in the parametric analysis.

2. Methods

2.1. Economic feasibility evaluation

The Net Present Value (NPV) of the dryer investment is used to evaluate the benefits from drying and it has been computed as:

$$NPV = \sum_{t=0}^{k} \frac{R_{steam-incr,y} - C_{O\&M,dryer}}{(1+i)^t} - C_{INV,dryer} \tag{1}$$

where $R_{steam-incr,y}$ [€/y], is the revenue due to the increased steam production; $C_{O\&M,dryer}$ [€/y] are the dryer operation and management costs; and $C_{INV,dryer}$ [€] is the capital cost of the dryer. Capital is amortised over k years of operation at a nominal interest rate of i% per year (assumed by hypothesis in the range of 5–10%). The revenue due to the increased steam production is computed as:

$$R_{steam-incr,y} = \underbrace{C_{steam}}_{\frac{c€}{MJ}} \underbrace{\Delta G_{steam}}_{\frac{kg}{s}} \underbrace{\Delta h_{steam}}_{\frac{kJ}{kg}} \underbrace{3600}_{\frac{s}{h}} \underbrace{\tau_{operation}}_{\frac{h}{y}} \tag{2}$$

where C_{steam} is the steam economic value; ΔG_{steam} is the variation in the steam production due to the use of dried fuel; h its enthalpy content and $\tau_{operation}$ is the operational time of the plant (dryer and combustion system). The heat source characteristics for the dryer operation and the economic parameters are detailed in the next section.

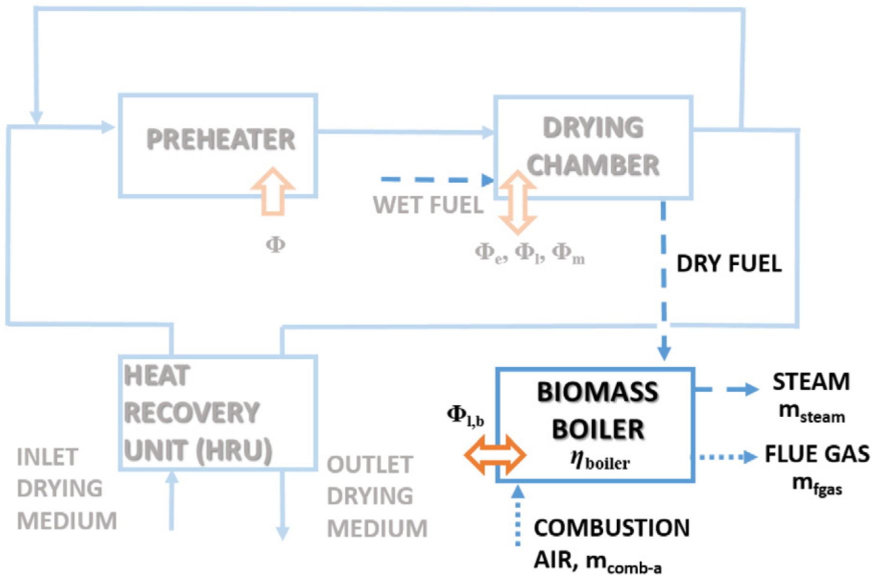

Fig. 3. Overview of the system studied, with its boundaries.

The model considers an average of the results of computing the dryer investment cost $C_{INV,dryer}$ [€] with two industrial dryer system cost functions with the related hypotheses, adapted from [15,21,23]:

$$C_{INV,dryer}[€] = \frac{C_{INV,dryer,1} + C_{INV,dryer,2}}{2}. \quad (3)$$

Table 3
Variables for the combustion and steam production sub-model.

Input parameters		
Biomass fuel		Wood chips
LHV	$[MJ/kg_{daf}]$	$f(M_{w,2})$
C	$[\%_{w,daf}]$	49.60
H	$[\%_{w,daf}]$	6.20
O	$[\%_{w,daf}]$	44.20
S	$[\%_{w,daf}]$	0.00
N	$[\%_{w,daf}]$	0.00
Combustion		
Air inlet T_{comb-a}	$[°C]$	25.0
Air inlet p_{comb-a}	$[kPa]$	101.32
Fuel dry mass flow $m_{w,2}$[a]	$[t/h]$	1.0–10.0
Fuel moisture (in) $M_{w,2}$[a]	$[\%_{w,wb}]$	10–60
Comb. heat th. losses $\Phi_{l,b}$	$[\% LHV_{daf}]$	5.0
Air excess ε[b]	$[-]$	1.60
Recovery efficiency ε_{hx}	$[-]$	0.90
Boiler approach point T_{AP}	$[°C]$	20.0
Boiler pressure level (single) p_{steam}	$[bar]$	20.0
Output parameters		
Limiting fuel moisture content M_{lim}	$[\%_{w,daf}]$	
Flue gas comp. $[O_2, N_2, CO_2, H_2O, NO_2]$	$[\% mol/mol]$	
Steam mass flow m_{steam}	$[kg/s]$	
Ideal combustion efficiency[c] η_{comb-a}	$[-]$	
Ideal boiler efficiency[d] η_{boiler}	$[-]$	

[a] From the dryer model output.
[b] A single total air excess value.
[c] Computed as the combustion products enthalpy content over the lower calorific value of the biomass fuel entering the furnace.
[d] Computed as the energy in the live steam, considering the reference for enthalpy at ambient temperature.

First, the cost of an industrial dryer can be expressed as a function of the dryer area, A_d $[m^2]$ [21]:

$$C_{INV,dryer,1}[€] = 7820(2.79A_d + 52.2)^{0.863}. \quad (4)$$

The second dryer investment cost $C_{INV,dryer,2}$ is evaluated considering also some additional costs, by using a multiplying factor $G \geq 1$, named as the Lang Factor [23]. This factor G is set at 1.60 on the basis of the following adding cost values: electrical (+0.10), instrumentation (+0.10), lagging (+0.05), civil work (+0.15), installation (+0.20) [23].

$$C_{INV,dryer,2}[€] = G\sum C_{equipments}. \quad (5)$$

The equipment cost is computed as follows [23]:

$$C_{equipments}[€] = C_{conveyor} + C_{hx} + C_{cover} + C_{drym-duct} + C_{fan} = \\ = 2700A_d + 660A_{hx}^{0.7} + 1200A_c^{0.5} + 3770m_{dm}^{0.5} + 0.9\Delta pm_{dm}^{0.7} \quad (6)$$

where A_d, A_{hx}, and A_c are respectively the conveyor dryer cross sectional area, the heat transfer area of the heat exchangers in the system (e.g. heat recovery units, but not the dryer) and the dryer cover cross sectional area. The height of the cover is assumed to be 6 m (industrial dryers application). m_{dm} is the drying medium mass flow $[kg/s]$ and Δp $[Pa]$ is the drying medium pressure drop across the drying stage.

The values of the area can be computed as a function of the flow (density, velocity) or heat transfer (logarithmic mean temperature, heat exchange factor) variables from the dryer system model. A single-stage air drying system is considered in this study. It has lower drying costs with respect to the more efficient multi-stage dryers [23], consequently it is supposed to be a more suitable choice for small-scale systems.

2.2. Single stage drying system model

The single stage air dryer is modelled as a two-block system: a preheater to produce the drying medium (heated from ambient temperature using a hot primary source) [10,15] at the proper thermodynamic conditions and a drying chamber in which energy and mass exchanges between the fuel and the drying medium occur. The heat

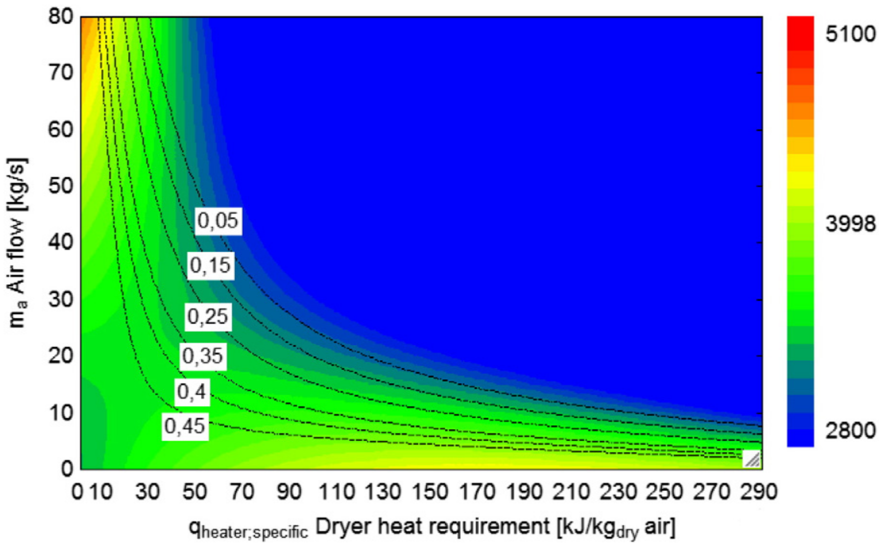

Fig. 4. Operational map with the dryer specific heat consumption as a function of the air flow at the pre-heater inlet, of the pre-heater heat flux $q_{h,s}$ and the fuel moisture at the dryer outlet 0.45–0.05 [% $_{w,wb.}$] (black isolines). Operations for drying 1 kg/s of dry biomass fuel.

for processing the drying air could come from, for example, the boiler or, when available, from other processes. This heat source is modelled as an operational cost.

In Fig. 2, the dry air mass flow is indicated with m_{dm}. It is heated in a Heat Recovery Unit (HRU, 1–2) and in the main heat exchanger (3–4) with the heat flux Φ. Hot dry air goes through in the drying chamber (4–5), where losses Φ_l, mechanical work Φ_m, and electrical work Φ_e are considered. Wet air can be partially recirculated (R is the recirculation factor), then sent to the HRU (7–8) and finally to the exhaust. The importance of the saturated air recirculation lies in three reasons: increased energy efficiency, possible optimization of the factor R to maximize the moisture removal from the fuel, and the issues of control (e.g. fire hazards). However, in case of simpler systems with no recirculation, the input factor R in the model can be set to 0%.

The behaviour of the systems is studied with the software Engineering Equation Solver©. The main equations are mass, energy and exergy balances applied to the systems, adapted from [22]. The thermodynamic and psychometric properties are evaluated with the specific software functions. The key variables considered are reported in Table 2.

2.3. Simplified model for the steam boiler

In order to evaluate the advantage of burning dry fuel in the combustion system, a simple combustion and steam production sub-model has been developed. The two sub-models are coupled as represented in Fig. 3.

The model parameters for the boiler sub-model are summarised in Table 3. During combustion, the biomass undergoes internal drying, devolatilisation and char combustion. The devolatilisation and the secondary combustion of the oxidation products can be modelled, in a simplified approach, with chemical equilibrium computations, as reported in the specific literature [24–28]. In this work, the gasification product composition is computed by minimization of the Gibbs free energy of the chemical system. Carbon in the residual char is oxidized into carbon monoxide and carbon dioxide. The volatile gas produced are then completely oxidized in the secondary combustion zone, an air excess zone. Flue gas recirculation, preheated combustion air and air staging below the grate are not investigated. The steam production is estimated by considering that all the heat produced in the combustion

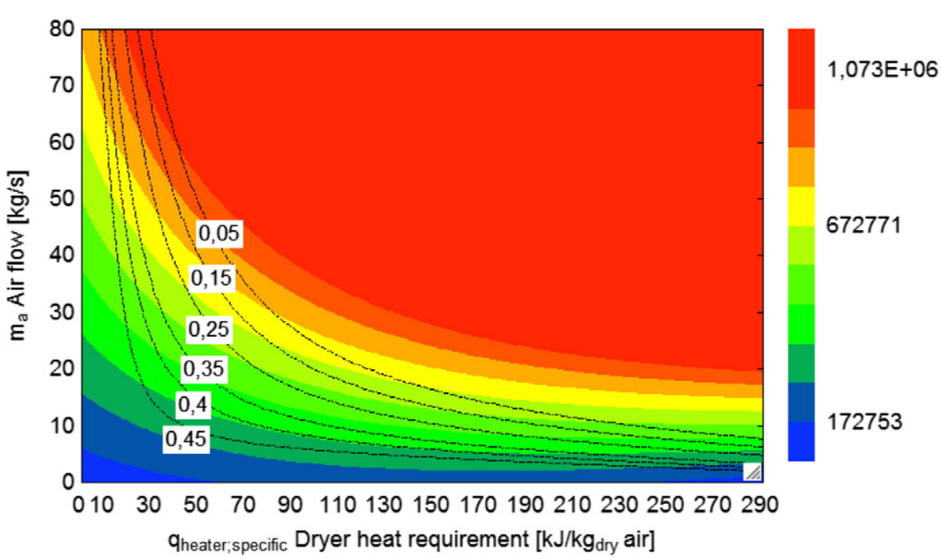

Fig. 5. Operational map with the capital cost of the dryer as a function of the air flow at the pre-heater inlet, of the pre-heater heat flux $q_{h,s}$ and the fuel moisture at the dryer outlet 0.45–0.05 [% $_{w,wb.}$] (black isolines). The dryer estimated investment cost increases for higher drying medium flow rates and higher heat flows to produce the drying medium supplied.

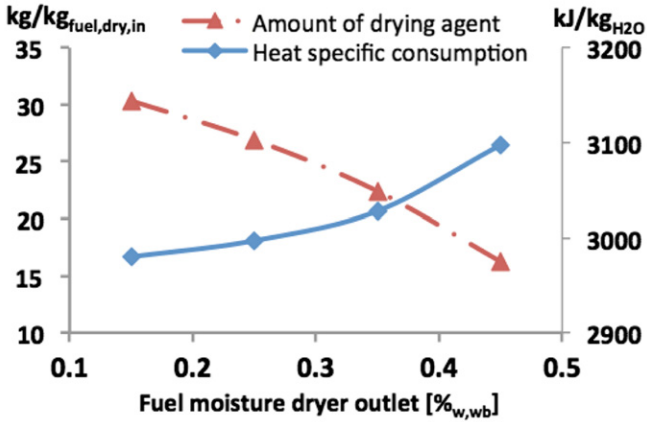

Fig. 6. Drying medium mass flow required to dry the fuel (left) and dryer heat specific consumptions (right). These trends, representing specific quantities, are valid for all the system sizes analysed.

is exchanged in the convective pass of the boiler. Losses within the heat transfer are modelled by setting a recovery efficiency of the combustion gas energy content (see Table 3).

The model is able to determine the moisture content limit for self-sustaining combustion, defined as the fuel moisture content for which the primary combustion step (on the grate) is no more endothermic. The computed limiting moisture value is about 60%$_{w,wb.}$ with the fuel input data selected.

3. Results and discussion

3.1. Modelling results for the single stage drying system

Operational maps of the single stage drying system have been built to present:

- The heat consumption [kJ/kg_{H_2O} evaporated] (Fig. 4), which is an indication of the thermal efficiency of the system, and the specific irreversibility rate [kJ/kg_{H_2O} evaporated] (not shown here), which is a measure of the exergy efficiency of the dryer [22].
- The estimated $C_{INV,dryer}$ [€] (Fig. 5).

These parameters are presented as a function of the drying medium flow rate m_{dm} [m^3/s], the specific energy flux to heat the air medium in the heat exchanger $q_{h,s}$ [$kJ/kg_{dry,air}$] and the moisture of the fuel at the outlet of the dryer $M_{w,2}$ [% $_{w,wb.}$].

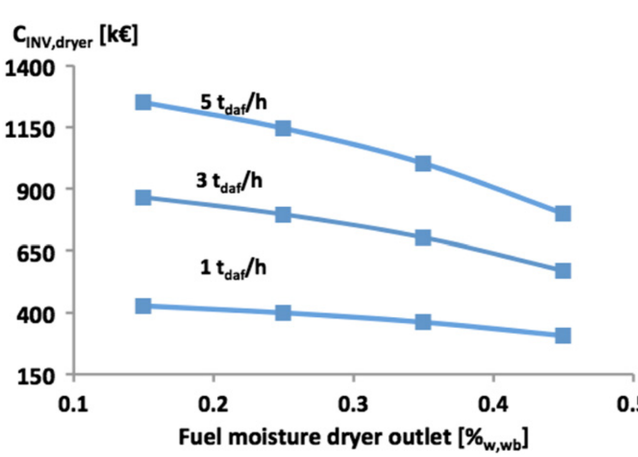

Fig. 7. Dryers investment cost as function of the system size.

Table 4
Increment in steam production as function of the fuel drying, according to the simplified combustion model.

Drying (in/out)	Steam prod. $\dot{m}_{steam}$
0.60–0.40% $_{w,wb.}$	+7.4%
0.60–0.30% $_{w,wb.}$	+8.0%
0.60–0.20% $_{w,wb.}$	+8.7%
0.60–0.15% $_{w,wb.}$	+8.9%
0.60–0.10% $_{w,wb.}$	+9.1%

For a given drying air flow rate, the moisture removal from the fuel is higher for high dryer specific heat requirements (Fig. 4). The heat specific consumptions are minimized for high moisture removal (Fig. 4). For medium heat specific consumption and air flows, the computed air temperature after the drying step (state 5, Fig. 2(a)) is in the range 30–70 °C.

From Fig. 4, it is possible to assess that, given the final moisture content after drying, optimal couples of variables can be selected to maximize the dryer energy efficiency. According to the model results, the operational area that corresponds to low specific consumption and irreversibility is defined by the limits 70–190 kJ/kg provided at the heat exchanger and 10–30 m^3/s of drying air flow.

The capital cost of the dryer increases in case of high drying air flows, because the cost is related to the cross sectional area of the dryer (Fig. 5). For a given drying air flow rate, the cost decreases in the case of higher specific heat flows provided to the heat exchanger to produce the drying air. From Fig. 5 it is possible to assess that, given the final õmoisture content, optimal couples of variables can be selected to minimize the dryer cost.

From the dryer simplified modelling results, two additional preliminary conclusions can be drawn:

1. The dryer energetic efficiency rise, when increasing the size of the system and the mass of fuel dried.
2. The influence of the recirculation factor on the system performances can be positive or negative, depending on the operating parameters. An optimum recirculation factor R $_{opt}$ that minimizes the fuel moisture content at the dryer outlet (or the heat consumption) exists and can be computed with the model.

According to the model results (Fig. 6), the drying medium mass flow rates required to dry the fuel increase when increasing the moisture removal. Additionally, higher moisture removal allows a decrease in the specific heat consumption. The medium requirements are related to the recirculation of the saturated air (set to a fixed percentage, see Table 2), which reduces the intake of ambient air flow rate. Furthermore, the air drying system specific heat consumption is sensitive to

Table 5
Main parameters for the economic modelling. The $C_{O\ \&M,dryer}$ are expressed as % of the $C_{INV,dryer}$.

Parameter	S1	S2	S3	S4	S5
$C_{steam}\left[\frac{c€}{MJ}\right]$	1.5	1.5	1.0	Variable	1.3
$C_{O\ \&M,dryer}$[%]	15	10	10	8	Variable
$\tau_{operation}\left[\frac{h}{y}\right]$	8000	8000	6000	5000	Variable
i [%]	10	5	5	5	5

Table 6
Lower limit of the industrial combustion system size [t_{daf}/h] for which the drying system is suitable (payback time of 5 years).

	S1	S2	S3	S4	S5
m_{lim}	1.8	1.0	[a]	(2.0 c€/MJ) 1.2 (1.3 c€/MJ) 4.9 (1.0 c€/MJ)[a]	See Fig. 10

[a] Larger than 6.0 t_{daf}/h.

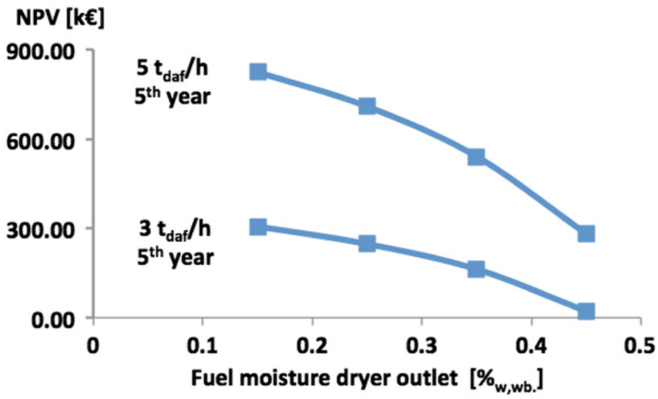

Fig. 8. Scenario S1. Dryers cumulated NPV as function of the moisture removal from the fuel.

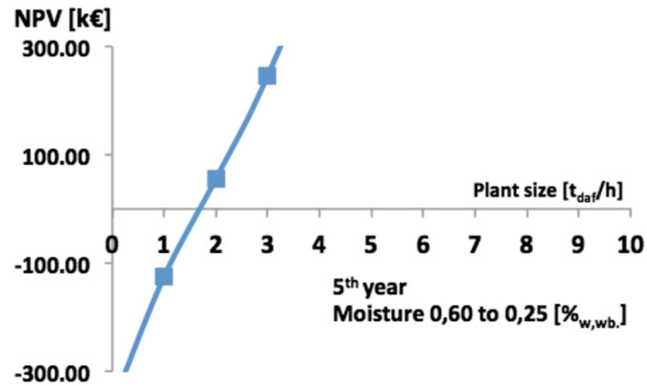

Fig. 9. Advisory tool result (scenario S1).

the losses associated to the additional heat exchangers in the system (air pre-heater and HRU).

The dryer investment costs are computed varying the fuel mass flow rate in the range 1–6 t_{daf}/h. The cost $C_{INV,dryer}$ increases in case of higher moisture removal and is higher for larger sizes (Fig. 7).

3.2. Modelling results for the steam boiler system

Confirming the expected behaviour, the ideal combustion efficiency decreases when the moisture content rises, due to a dilution effect. According to the simplified model, burning dry fuel allows a moderate increase in the steam production (<10% relative steam production increment, when drying from 60 $\%_{w,wb}$ to 10 $\%_{w,wb}$), as is reported in Table 4. With the simplifications considered, the feed rate has no direct influence in the relative steam production increment. Experimental data on the increased steam boiler efficiency due to lower moisture contents are available, for example in [20], and a reasonable agreement is found.

The heat flux used for drying is not accounted for within the energy balance of the combustion plant. The energy requirements of the dryer are evaluated in economic terms as operation (O&M) costs. The results of the next section allow the assessment of the feasibility of the dryer coupled with the steam boiler, as a function of the system size.

3.3. Economic coupling of the two systems

The increased steam production is evaluated in economic terms and compared with the investment and operational costs of the drying technology. The evaluation is performed without considering the costs of biomass purchasing (the feedstock cost at the system inlet, can depend on its moisture content).

If focussing on the economic analysis, the variations of some parameters previously introduced (steam selling price, operation and maintenance costs, dryer operational time and interest rate) allow presenting different scenarios (S), as shown in Table 5. The steam economic value is based on its energy content and is assumed by hypothesis[1] in the range between 1.0 and 2.0 c€/MJ. The dryer O&M costs (including the heat source for drying) are chosen as a fraction of its investment cost, decreasing from S1 to S4. High O&M costs correspond to high cost of the heat for drying production, or high price of the heat source for drying. Low O&M costs correspond to a high availability of thermal sources to produce the drying medium (i.e. CHP or low-exergy process heat). The dryer operation time chosen for S1 corresponds to a high dryer and boiler availability factor and is assumed to decrease for S3 and S4. In the scenario S5, the minimum system size is expressed as a function of the cost of the heat source for drying and of the operation time.

Considering the results for the scenario S1, the cumulated NPV of the investment is reported as a function of the moisture removal from the fuel in Fig. 8. For the hypotheses considered, the net present value is higher in case of an increasing moisture removal: it is better to dry as much as possible.

For the following results, by hypothesis,[2] a target final moisture content of 25% $_{w,wb.}$ at the combustion chamber inlet (dryer outlet) is set.

These results evidence that there is a lower limit plant size for which the increment in the steam production does not compensate (for example, in a limit payback time of 5 years) the investment and operational costs to sustain the fuel drying (Fig. 9). This limit system size is represented graphically as the intersection of the cumulated NPV curves and the *x*-axis and it corresponds to the estimation of the smallest plant size for which the fuel drying is a feasible economic solution. As an example, with the stated hypotheses, fuel drying is feasible choosing air drying, if the boiler system size is larger than 1.78 t_{daf}/h (scenario S1).

The different scenarios are explored, see Table 6. In the scenario S2, decreased dryer operation and maintenance costs and a smaller interest rate are taken into account. Decreasing the utilization factor of the system remarkably changes dryer feasibility evaluation (scenario S3). The model results are quite sensitive to the steam price setting, as presented in the scenario S4.

In Fig. 10, the minimum plant size to recover the dryer investment is computed as a function of the system operating hours. Decreasing the availability and utilization factor of the system would increase the size of the smallest system for which drying is feasible. According to the model results, in case of a small scale biomass combustion boiler with fuel drying, high production availability must be ensured to recover the dryer investment in 5 years of operations (S5, Fig. 10). As an example, with the stated hypotheses, for a system processing 1.5 t_{daf}/h of wood chips, an air dryer (O&M costs set at 8%) would be economically feasible if the system availability is higher than about 8000 h/y. The influence of the drying heat source cost can also be studied (Fig. 10).

If considering the maintenance costs fixed at 4% of the investment costs [13], low operational costs can be set if the energy for producing the drying air is available within the system (i.e. in CHP configurations) or if producing the heat for drying the medium is thermally convenient, moreover if waste heat is available. High operational costs have to be set if waste heat sources are not available or high exergy energy has to be used,[3] i.e. with a decrease of the boiler steam output. However, the precise estimation of this cost will depend on the specific configuration to be analysed.

[1] It can be computed, in a first estimation, considering the fuel cost in [c€/*MJ*] and an average combustion efficiency.

[2] In case of enhanced drying (below 10%$_{w,wb.}$), the NPV could decrease, because of the dryer emission issues and secondary effects (as the fire risk).

[3] In that case, other possible solutions for using the heat source should also be discussed.

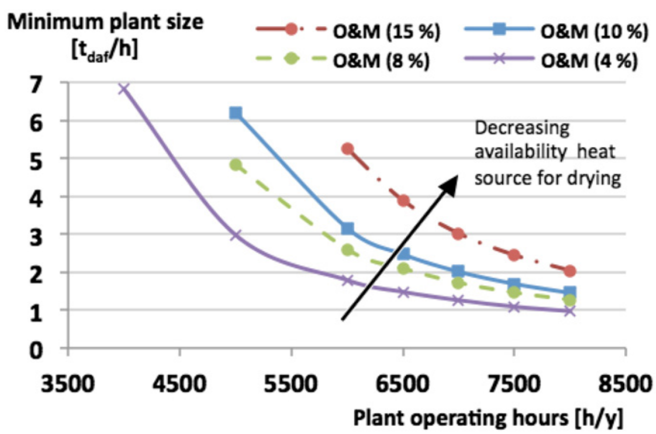

Fig. 10. Results of the modelling for scenario S5. High operational costs would correspond to low availability of thermal sources for drying the fuel.

4. Conclusions

It is widely known that a reduced biomass moisture positively impacts the combustion system performances, but the need for dry biomass feedstock requires large energy and capital costs on small-to-medium scale biomass plants. The main objective of the study is to evaluate in which terms an air-dryer investment is pertinent for small-scale biomass steam boiler. A model to evaluate the component economic feasibility was built. Two energy systems are modelled: the dryer sub-model (with air as drying medium) and a steam boiler simplified sub-model. Thanks to the first one, the drying investment costs are assessed with correlations from the literature and as a function of the operating parameters. With the second sub-model, the effects of moisture on the combustion behaviour and boiler operations are verified. Both models can be applied to different feedstock characteristics.

The modelling approach allows the assessment of the plant size for which the drying system is not economically affordable. The results are presented in five examples (scenarios) and point out the influence of the system size and of the plant availability on the dryer selection feasibility. Drying resulted in a suitable technical solution, even for small-scale systems, if considering a high plant availability. According to the model results (scenario S1), if the steam production plant operational time is above 8000 h/y, wood chips drying is feasible with air drying if the plant size is larger than 1.78 t_{daf}/h of fuel processed.

In this approach, the thermal integration between the drying processes and the steam power plant is not explored, and the heat source for drying is modelled as a variable O&M cost in the economic assessment, as a function of the plant size. A thermal balance for a specific small-scale biomass steam plant, without economic analysis, was developed by Ho Ting Luk et al. [10]. Illustrations for the dryer integration are presented in L. Fagernäs et al. [12].

Future investigations could improve the modelling approach by further describing the heat source for producing the drying medium. This O&M cost variable could be more explicitly computed as a function of the plant outputs (heat, steam, electricity costs), depending on the system thermal configuration. If the drying heat is coming from the boiler, this would allow to evaluate if the heat demand of the dryer can be directly covered by the flue gases or through steam extraction, depending on the case-specific energy balance. Finally, additional development would be reached if modelling other configurations for drying, such as flue gas and steam drying, and with a proper estimation of the costs thanks to updated functions.

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