CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761232

Design of Energy Systems with Biomass Utilization using Gasification and Torrefaction in Quicklime Plants

Styliani Chatzisakoula[a], Kyriakos Panopoulos[b], Panos Seferlis[a,*], Spyros Voutetakis[a]

[a]Department of Mechanical Engineering, Aristotle University of Thessaloniki, P.O. Box 484, 54124 Thessaloniki
[b]Chemical Process and Energy Resources Institute (C.P.E.R.I.), Centre for Research and Technology Hellas (CE.R.T.H.)
P.O. Box 60361, 57001, Thermi-Thessaloniki, Greece
seferlis@auth.gr

The aim of this paper is to investigate the benefits of fuel switching to biomass in energy intensive industries such as quicklime plants. Biomass gasification and torrefaction are biomass processing technologies utilized in offering an alternative thermal source, partially replacing fossil fuels. Such transition facilitates the drastic reduction of emitted CO_2 and other hazardous substances but is accompanied by significant additional process infrastructure requirements. Process simulation based analysis enables the evaluation and assessment of the heat integration solutions for the renewable fuel transformation technology with the existing production unit. Definitely, a higher overall efficiency can be achieved with biomass gasification based on a carbon emissions analysis. However, torrefaction improves plant flexibility, especially under intermittent or highly variable biomass supply due to the ability of the plant to store effectively the processed solid fuel.

1. Introduction

Quicklime production is an intensive energy process with high CO_2 emitting loads. Crashed limestone is heated in a kiln reactor, where is calcinated to CaO with the release of CO_2. Typically, the heat required for the calcination reaction is generated through combustion of fuel, such as petroleum coke. The high CO_2 emissions are due to both combustion and the calcination reaction with an estimate of 973 kg CO_2 released per ton of quicklime produced (Sagastume et al., 2012). In order to reduce CO_2 emissions, part of the required thermal heat can be replaced by biomass gasification or torrefaction derivatives, which are attractive alternatives for fossil fuels substitution. The investigation of the integration of gasification and torrefaction processes in energy intensive industries is the main focus of this work. Utilization of biomass has an almost zero balance of carbon dioxide and therefore its contribution to the greenhouse effect is minimal (Ulsu et al., 2008). A comprehensive overview of the possibilities leading to the reduction of the emitted carbon pollutants from quicklime industry is provided by incorporating fuel switching to either syngas or torrefied biomass. The evaluation of the thermal efficiency of lime kilns has been the subject of several studies (Gutierrez et al., 2013). Biomass gasification simulation was studied by Sun et al. (2014), who used sensitivity analysis to investigate the process operating conditions using validated experimental data. Joshi et al. (2015) simulated a steady state torrefaction model under different process temperatures. Martinez et al. (2016) studied biomass torrefaction by means of kinetics with thermogravimetric analysis taking under consideration the process residence time. A kinetic scheme was developed by Anca-Couce et al. (2014) for the prediction of the solid product composition. In this particular study, both residence time and process temperature effects on the final product were explored. Rentizelas and Li (2016) focused on carbon emissions and investigated various co-firing ratios (i.e. ratio of pet coke replaced with biomass based fuel) by partially replacing pet coke by biomass derived fuels. Despite the rich literature on the gasification and torrefaction processes, their integration in energy intensive plants for the replacement of fossil fuels has not been explored adequately, especially in quicklime plants. This work aims to unveil the interactions between the biomass processing steps and the production line in quicklime plants and further investigate the feasibility and the potential benefits from fuel switching to biomass based fuels.

Please cite this article as: Chatzisakoula S., Panopoulos K., Seferlis P., Voutetakis S., 2017, Design of energy systems with biomass utilization using gasification and torrefaction in quicklime plants, Chemical Engineering Transactions, 61, 1405-1410 DOI:10.3303/CET1761232

2. Process modelling description

Simulation models for the calcination process using combustion of a predefined mixture of pet coke and biomass derived fuel, biomass gasification and biomass torrefaction process have been developed and validated using literature experimental data.

2.1 Quicklime production model

The quicklime kiln has been modelled as a reactor, where the calcination reaction ($CaCO_3 \rightarrow CaO + CO_2$) takes place at around 900 °C along with the combustion of the selected fuel, considered as a mixture of pet coke and biomass derived fuel. Most quicklime industrial units use pet coke, a refinery by-product, with high sulphur and heavy metals concentration, such as aluminium, calcium and iron. The typical composition of pet coke is shown in Table 1. The main steps of the quicklime productions process are shown in Figure 1.

Table 1: Ultimate and proximate analysis of pet coke

Ultimate Analysis (% w/w db)					Proximate Analysis (% w/w db)			HHV
C	N	H	O	S	FC	VM	Ash	[kJ/kg dry]
84,41	2,35	2,12	0,82	6,74	91,5	4,94	1,32	31.308

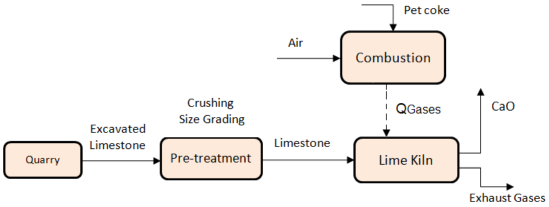


Figure 1: Quicklime production process steps.

The emissions from quicklime production are emanating from both fuel combustion and the release of CO_2 from the decomposition of $CaCO_3$. In addition, CO_2 emission quotas on industrial units make the replacement of fossil fuels by renewable energy sources a necessity. The choice of fuel is an important factor that strongly affects production cost by as much as 40 - 50 %. The system is assumed to operate at steady state with a continuous flow process. The input and output gases are assumed as ideal gases, the variation of the potential and kinetic energy is neglected and pet coke composition is presumed constant during the process.

2.2 Biomass gasification model

Biomass gasification is an alternative process to convert biomass to high energy content fuels. Biomass is catalytically converted into a gas mixture, rich in H_2 and CO, known as syngas, suitable for the production of both power and heat. A biomass gasification process model has been developed under steady state conditions, where both endothermic and exothermic reactions occur as described by Sun et al. (2014). Char, which is about 2 % of the total carbon, is considered to have the properties of graphite C(s) that facilitates the simulation model without compromising the accuracy of the model predictions. The case of biomass based on straw is considered with its typical composition given in Table 2. The integrated system of biomass drying and gasification in a quicklime kiln is shown in Figure 2. Drying in the gasification process occurs at relatively lower temperatures in the range of 100 - 150 °C. Heat Integration is accomplished through the utilization of the heat content of the flue gas in the kiln that is available at a temperature of approximately 350 °C. The heat demand of the dryer is calculated at 1 MW and almost 70 % of it is covered by the quicklime kiln heat in the flue gas.

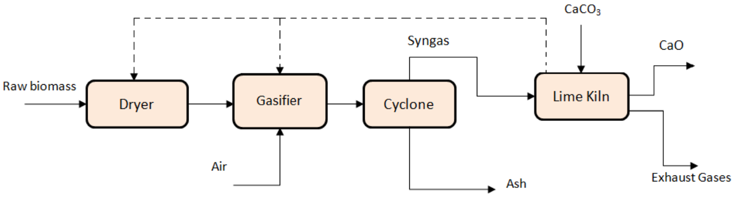
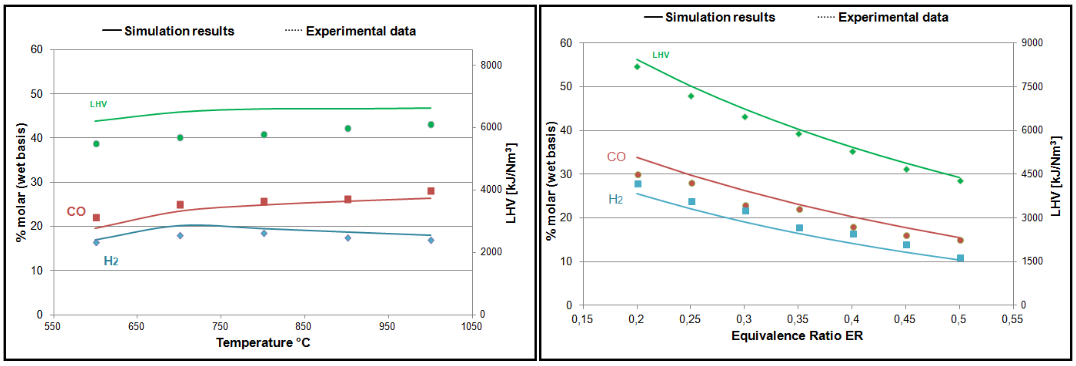


Figure 2: Integrated system of lime kiln integrated with biomass gasification.

Table 2: Composition of straw based biomass

Ultimate Analysis (% w/w db)					Proximate Analysis (% w/w db)			HHV
C	N	H	O	S	FC	VM	Ash	[kJ/kg dry]
47.53	0.63	6.41	45.56	0.1	19.26	80.88	4.01	18

The biomass gasification simulation model has been validated using experimental data (Sun et al., 2014) using process temperature and equivalence ratio (i.e. biomass to oxygen ratio, ER) as the independent variables. Figure 3 shows the effect of process temperature and ER on syngas product composition. As observed, gasification temperature does not affect gas composition, however further reduction in gasification temperature may result in incomplete process of the biomass giving rise to the emission of tars. The increase of ER causes an increase in CO_2 and H_2O with a subsequent decrease in the high heating value (HHV).



(a) (b)

Figure 3: Model validation of biomass gasification on (a) process temperature and (b) equivalence ratio.

2.3 Biomass torrefaction model

Torrefaction is a thermal process carried out at a temperature range of 200-300 °C, with residence time ranging from few minutes to several hours and under the absence of oxygen. The advantages of torrefaction include the increase of the product calorific value, improvement of the grindability of the solid product, increase of energy density and the production of fuels with uniform properties. The torrefied biomass has hydrophobic characteristics that make storage more attractive than raw biomass and further increases the C/O ratio in the fuel resulting in improved efficiency. The simulation process system is modelled taking under consideration process temperature and residence time as the main operating factors and is able to predict accurately the flow and composition of the final products. According to Bergman et al. (2005), the recommended torrefaction temperature level should not exceed 300 °C as biomass may release too much volatiles and carbonization of polymers may be enhanced, two undesirable effects. Reaction time has a smaller influence on the mass and energy yields than torrefaction temperature. The simulated results have been validated using published data (Clausen, 2014) regarding the composition of the torrefied product as shown in Table 3 for straw based biomass. The simulated model is able to capture the heating value of the product quite accurately. The integrated system of biomass drying and torrefaction with a quicklime kiln is shown in Figure 4. Heat integration can be accomplished using kiln flue gas waste heat in the biomass dryer and the torrefaction reactor heating. An energy recovery heat exchanger is used to recover heat from hot flue gases of lime kiln, that are at about 350 °C, to preheat the incoming biomass to the torrefactor, at 270 °C. The heat demand of the torrefactor is calculated at 2 MW and almost 40% is covered by the lime kiln heat recovery.

Table 3: Ultimate and proximate analysis of straw under different conditions (temperature [°C] / time [min])

	Ultimate Analysis (% w/w db)				Proximate Analysis (% w/w db)			
	C	N	H	O	Fixed Carbon	Volatile	Ash	HHV
Raw	47.53±0.28	0.63±0.05	6.41±0.01	45.56±0.53	19.26±0.02	80.88±0.01	4.01±0.02	17.81±0.13
240/ 60	47.39±0.01	0.69±0.01	6.43±0.37	45.28±0.34	20.72±0.4	79.28±0.41	4.75±0.01	17.92±0.01
240/120	47.92±0.12	0.65±0.01	6.31±0.05	44.01±0.07	21.38±0.06	78.62±0.03	4.81±0.02	17.98±0.06
270/60	52.87±0.01	0.82±0.01	6.18±0.14	40.31±0.16	29.85±0.22	71.03±0.16	5.63±0.06	20.41±0.07
270/120	53.82±0.16	0.75±0.01	6.02±0.02	39.32±0.23	29.56±0.01	70.12±0.15	5.81±0.02	20.53±0.06

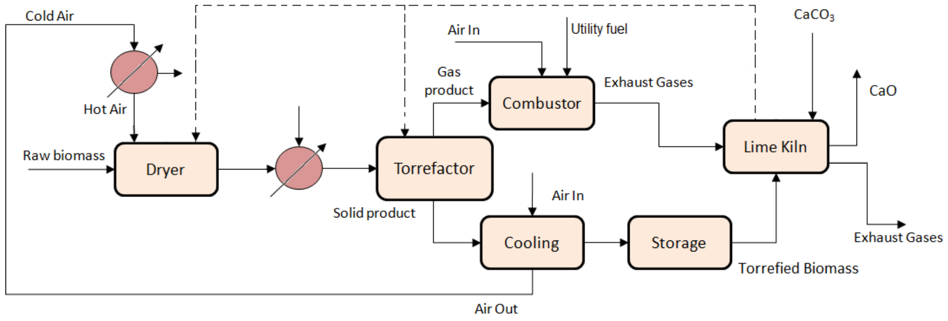


Figure 4: Integrated system of lime kiln with biomass torrefaction.

2.4 Biomass supply and utilization

Agricultural biomass is characterized by seasonal availability as harvesting occurs at specific time periods during a year. A lot of research work has been conducted regarding the biomass supply chain investigating in particular biomass periodicity and its implications in the total operating cost. Rentizelas and Li (2016) concluded that a multi-source biomass strategy is more advantageous because it leads to significant cost savings compared to a single-source biomass approach. To this end, a model is developed for the integrated biomass processing – quicklime production plant that accounts for biomass procurement, storage, and utilization under variable biomass availability conditions. Torrefaction allows the production of larger amounts of torrefied product than those required for the calcination reaction. The surplus torrefied fuel can be then stored for subsequent use during periods, where biomass availability is low and supply procurement costs are high. On the contrary, the biomass gasification product is gaseous and storage is more difficult and costly. In such a case, crude biomass is stored for subsequent use in the gasification process. The difference between storing torrefied and crude biomass is the energy density per mass that results in higher required storage volume. On the specific case study, it is assumed that biomass supply and price can vary considerably between time periods reflecting on a realistic situation. Simulation time period is defined as a reasonable time span, suitable to represent the state of the production system. Specifically, during the time periods of low biomass availability, procurement cost is significantly higher than during periods of high biomass availability. A linear programming (LP) problem is therefore developed for the calculation of the optimal schedule of biomass procurement and utilization based on the minimization of the overall operating cost. The model provides a global optimal solution over a six period planning horizon by minimizing the objective function consisted of procurement and storage cost for biomass as expressed in Eq(1). The duration of a single time period for the simulation is selected as one month.

$$\min \mathrm{f}_{\mathrm{Cost}} = \sum_{\mathrm{i}=1}^{\mathrm{NP}} \Bigg[\mathrm{pc}_{\mathrm{i}}[t] \cdot \mathrm{C}_{\mathrm{pc}} \left[\frac{€}{t}\right] + \mathrm{biom}_{\mathrm{i}}[t] \cdot \mathrm{C}_{\mathrm{biom}} \left[\frac{€}{t}\right] + \mathrm{biom}_{\mathrm{total,i}}[t] \cdot \frac{C_{bstor}\left[\frac{€}{m^3}\right]}{D_{biom}\left[\frac{t}{m^3}\right]} + \mathrm{torref}_{\mathrm{total,i}}[t] \cdot \frac{C_{tstor}\left[\frac{€}{m^3}\right]}{D_{torref}\left[\frac{t}{m^3}\right]} \Bigg] \tag{1}$$

Symbols C_{pc}, C_{biom}, are the fuel procurement costs per ton, whereas C_{bstor} and C_{tstor} are the cost coefficients for biomass and torrefied product storage as provided in Table 4. Symbols pc_i and $biom_i$ are the mass of procured fuels and $biom_{total,i}$ and $torref_{total,i}$ are the stored crude biomass and torrefied fuel stored in tons for the i-th period. In addition, equality constraints related to energy and material balance of raw and torrefied biomass are imposed. Inequality constraints are also applied concerning storage capacity of the plant.

$$\mathrm{biom}_{\mathrm{total,i}} = \mathrm{biom}_{\mathrm{total,i-1}} + \mathrm{biom}_{\mathrm{i}} - \mathrm{biom}_{\mathrm{used,i}} \tag{2}$$

$$\mathrm{torref}_{\mathrm{total,i}} = \mathrm{torref}_{\mathrm{total,i-1}} + \mathrm{torref}_{\mathrm{i}} - \mathrm{torref}_{\mathrm{used,i}} \ , \quad \mathrm{torref}_{\mathrm{i}} = \mathrm{biom}_{\mathrm{used,i}} \cdot coef_{biom2torr} \tag{3}$$

where $biom_{used,i}$ and $torref_{used,i}$ represent the utilized biomass and torrefied biomass in the calcination kiln for the i-th period, respectively. Symbol $coef_{biom2torref}$ is the coefficient of conversion for the production of torrefied biomass calculated from the simulation model equal to 0.78 in tons of torrified per ton of crude biomass.

Eq(4) is an environmental constraint imposed that limits CO_2 emissions produced per time period defined by environmental regulations and other community policies. Sole pet coke combustion violates the permitted CO_2 emissions and therefore the incorporation of thermochemical biomass processing is absolutely necessary.

$$E_{permit,i} \geq biom_{used,i} \cdot E_{biom2torr} + torr_{used,i} \cdot E_{torr} + pc_i \cdot E_{pc} \tag{4}$$

Symbols $E_{biom2torr}$, E_{torr}, and E_{pc} are the CO_2 emissions for torrefaction, combustion of torrefied biomass and pet coke combustion in tons of CO_2 released per ton of used fuel and provided in Table 4.

Table 4: Fuels characteristics (Rentizelas and Li, 2016)

	Pet coke	Raw biomass	Torrefied biomass
Density [t / m^3]		0.3	0.6
Energy density [GJ / m^3]		7.6	15.4
Heating Value [GJ / t]	31.3	17.8	20.7
Biomass Availability	Year-round	3 months periodicity	Year-round
Purchasing cost [€ / t]	25	20-45	-
Storage cost [€ / m^3]	-	4.2	4.2
CO_2 emissions [t / t]	0.86	0.09 (torrefaction) 0.07 (gasification)	0.06

In the case of biomass gasification, it is important to note that syngas is a gaseous fuel and the storage capacity concerns only raw biomass. Therefore, sufficient storage capacity for raw biomass is necessary to accommodate seasonality in the biomass supply for the gasification utilization plant. Pet coke is a fuel that has high availability and regular supplies do not affect the operating costs. CO_2 emissions from biomass are almost zero as seen in Table 4 that constitutes an advantage comparing to pet coke combustion.

3. Results and discussion

In this study, carbon emission analysis has been used in order to investigate the benefits from the integration of biomass thermochemical process technologies, namely biomass gasification and biomass torrefaction, in in energy intensive industries. AspenPlus^{TM} is used to simulate these integrated processes and the input flows of the investigated scenarios of pet coke replacement are shown in Table 5.

Table 5: Input fuel flows of the studied scenarios [kg/s]

Biomass co-firing ratio (%)	0 %	20 %	40 %	60 %	80 %	100 %
Pet coke	25.3	20.24	15.18	10.12	5.06	0
Biomass (Gasification)	0	6.48	12.96	19.44	25.92	32.4
Biomass (Torrefaction)	0	4.42	8.84	13.26	17.68	22.1

Figure 5 indicates the annual reduction of CO_2 emissions for several co-firing scenarios covering a range from 20 % replacement to sole biomass based fuel utilization. The results clearly indicate that gasification process has lower carbon emissions compared to biomass torrefaction due to the higher process efficiency as shown in Table 6. Energy efficiency of each technology is defined as the ratio of the useful generated heat to the input energy content including all auxiliary fuel consumption as also indicated by Park et al. (2015).

Table 6: Process efficiency

Process	Pet coke combustion	Biomass Gasification	Biomass Torrefaction
	0.75	0.83	0.8

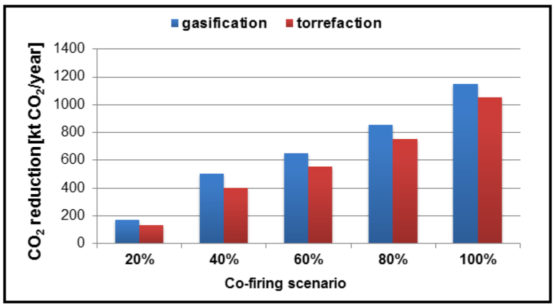
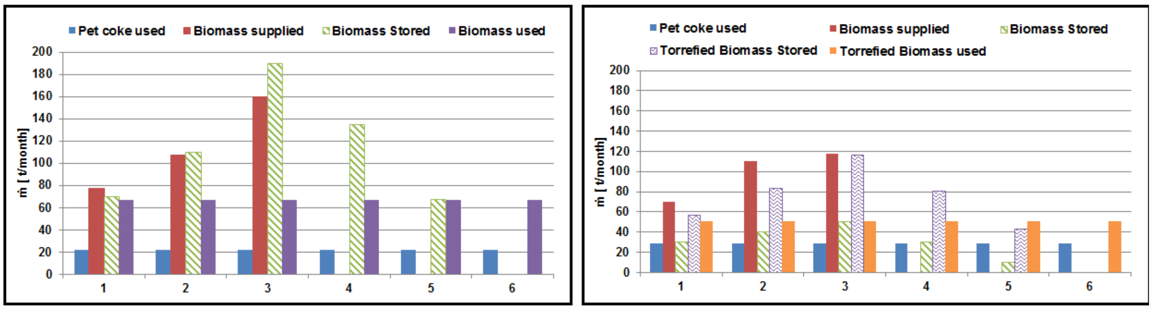


Figure 5: Annual CO_2 emissions reduction and efficiency for biomass (a) gasification and (b) torrefaction.

Regarding the employed scenario with variable biomass availability, Figure 6 shows that sufficient biomass is purchased during the first three months in order to cover the energy needs for the entire six months horizon.

The main advantage of the torrefaction process is that the significant increase in energy density achieved through the process, enables the cost effective storage of torrefied biomass. The optimal solution of the linear program of Eq(1) - Eq(4) concluded in lower overall operating cost in the case of biomass torrefaction compared to that of biomass gasification. More specifically, the operating cost of biomass gasification is estimated at 12,693 € for the entire time horizon, whereas the total cost for biomass torrefaction is 10,235 €.



(a) (b)

Figure 6: Fuels utilization and material storage for (a) biomass gasification and (b) biomass torrefaction.

4. Conclusion

It has been demonstrated that the integration of biomass gasification or torrefaction systems in energy intensive plants is beneficial for the drastic reduction of CO_2 emissions. Despite the slightly higher efficiency of the gasification process, biomass torrefaction exhibits higher flexibility in accommodating biomass supply variability effectively. This is mainly attributed to the ability to store the torrefied biomass with minimal cost due to the high energy density of the torrefied product. Reducing the process and storage cost of biomass feedstocks are both critical in developing a sustainable infrastructure capable of supplying an uninterrupted biomass flow to highly demanding production plants.

Acknowledgments

Part of this study has been funded from ROLINCAP.

References

Anca-Couce A., Mehrabian R., Scharler R., Obemberger I., 2014, Kinetic Scheme to Predict Product Composition of Biomass Torrefaction, Chemical Engineering Transactions, 37, 43-48.

Bergman P.C.A., Boersma A.R., Zwart R.W.R., Kiel J.H.A., 2005, Torrefaction for Biomass Co-Firing in Existing Coal-Fired Power Stations, ECN, Report ECN-C-05-013.

Clausen L.R., 2014, Integrated Torrefaction vs. External Torrefaction – A Thermodynamic Analysis for the Case of a Thermochemical Biorefinery, Energy, 77, 597-607.

Gutierrez A.S., Martinez J.B., Vandecasteele C., 2013, Energy and Exergy Assessments of a Lime Shaft Kiln, Applied Thermal Engineering, 51, 273-280.

Joshi Y., de Vries H., Woudstra T., de Jong W., 2015, Torrefaction: Unit Operation Modeling and Process Simulation, Applied Thermal Engineering, 74, 83-88.

Martinez M.G., Dupont C., Thiery S., Meyer X.M., Gourdon C., 2016, Characteristic Time Analysis of Biomass Torrefaction Phenomena – Application to Thermogravimetric Analysis Device, Chemical Engineering Transactions, 50, 61-66.

Park C., Zahid U., Lee S., Han C., 2015, Effect of Process Operating Conditions in the Biomass Torrefaction: A Simulation Study Using One-Dimensional Reactor and Process Model, Energy, 79, 127-139.

Rentizelas A.A., Li J., 2016, Technoeconomic and Carbon Emissions Analysis of Biomass Torrefaction Downstream in International Bioenergy Supply Chains for Co-Firing, Energy, 114, 129-142.

Sagastume A., Van Caneghem J., Cogollos J.B., Vandecasteele C., 2012, Evaluation of the Environmental Performance of Lime Performance of Lime Production in Cuba, J of Cleaner Production, 31, 126-136.

Sun L., Xu B., Smith R., 2014, Power and Chemical Production Analysis Based on Biomass Gasification Processes, Chemical Engineering Transactions, 38, 61-66.

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, 1206-1033.