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Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co-firing

Athanasios A. Rentzelas [a,*], Jun Li [b]

[a] Department of Design Manufacture and Engineering Management, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, UK
[b] Department of Chemical and Process Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, Glasgow, UK

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A B S T R A C T

Ambitious renewable energy targets in European countries drive an increasing biomass demand to a point where domestic resources are insufficient, leading to emergence of international bioenergy supply chains. This work aims to examine the feasibility of biomass torrefaction downstream in long-distance international bioenergy supply chains for co-firing and to investigate the effect of various biomass co-firing ratios on the whole supply and energy conversion system performance from a technical, environmental and economic aspect. A techno-economic analysis together with a CO_2 emissions assessment is performed, adopting a whole systems approach. In particular, Palm Kernel Shell biomass from Malaysia is considered for co-firing in UK. Findings indicate that downstream torrefaction is profitable under the current conditions for 100% biomass and marginally unprofitable for 50% biomass co-firing. The financial yield exhibits high sensitivity on the price of coal, biomass, Renewable Obligation Certificates, the torrefaction facility investment and biomass sea transportation costs. From an environmental perspective, higher co-firing ratios lead to higher emissions per unit of renewable energy generated. The findings can support policy makers and investors in adopting lower biomass co-firing ratios with torrefaction instead of 100% biomass conversion, leading to improved environmental benefits from a whole system's perspective.

1. Introduction

Biomass has been identified as one of the main energy sources to support the ambitious targets of increasing the share of renewable energy generation and reducing the Greenhouse Gas (GHG) emissions in many countries. The EU has set up the target for renewable energy contribution to 20% of the energy generation mix by the year 2020 and almost 51% of the increase from the 2014 level is expected to be achieved using biomass [1]. Similarly, the UK target for 15% renewable energy by 2020 will require half of the increase from the actual 5.2% in 2013 to be achieved using biomass [2]. Official sources estimate that 70%–87% of the UK biomass requirements in year 2030 will be covered by imported biomass, due to insufficient domestic sources [3]. If one takes into account that most Western European countries face a similar situation with continuously increasing biomass needs and limited domestic supply, it becomes clear that satisfying those needs requires long-distance transportation of biomass from locations beyond Europe.

Looking at the UK biomass-to-power sector in particular, as of April 2016 there were 2218 MWe of dedicated or co-firing biomass installed, with an additional 2938 MWe awaiting or under construction [4]. One of the most prominent players in this market is Drax power, with 1290 MWe operational and further 645 MWe awaiting construction, all of which concerns conversions of coal- to biomass-fuelled units. These figures show the extent of expansion of the biomass-to-power sector in the UK and therefore the scope for investigating the option of importing biomass resources for use in existing coal-powered units.

The need for long distance biomass transportation to Western Europe has been identified and received attention by the academic community during the last decade. Some researchers have focused on the techno-economic aspects of various biomass supply chain configurations from Latin America (eucalyptus) [5], Scandinavia or

* Corresponding author.
E-mail addresses: athanasios.rentzelas@strath.ac.uk (A.A. Rentzelas), jun.li@strath.ac.uk (J. Li).

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Eastern Europe to Western Europe (energy crops and forestry residues) [6] Australia, Canada and Russia to Western Europe [7], and Mozambique to Netherlands (eucalyptus and switchgrass) [8]. Researchers have also focused on the GHG effects and energy analysis of the respective supply chain from Malaysia (Palm Kernel Shells - PKS) and Canada (wood pellets) to Netherlands [9]. Currently biomass is commercially transported primarily from US and Canada to Western Europe, as well as from Eastern to Western Europe. The biomass transported is mainly forest residues, in the form of wood pellets or wood chips [5].

One of the potential pathways of generating energy from biomass is co-firing with fossil fuel sources at an existing power plant, usually a coal-fired plant. Co-firing can be considered as a transitional option towards a completely carbon-free power sector, offering advantages with respect to using biomass in dedicated power plants, such as higher thermal efficiency, lower capital costs, and less supply risk because the plant can revert to coal if biomass is insufficient [10]. This opens up an effective pathway to increase the biomass power capacity in the short-term and simplify the technical challenges [11].

However, biomass materials are significantly different from coal with respect to handing and combustion performance: biomass has lower energy density, higher moisture and volatile contents, higher chlorine and potassium contents than coal. Using untreated biomass for co-firing is thus technically complicated, as dedicated cutting mills, biomass burners, and in some cases changes in the boiler are required. The variable fuel quality displayed by biomass affects significantly the boiler performance; therefore, the co-firing ratios are currently kept at lower than 10% biomass input levels in most cases (energy basis) [10].

In this respect, torrefaction has been identified lately as a promising biomass pre-treatment option to allow increasing the co-firing ratio. By performing torrefaction, the tenacious nature of raw biomass is lost due to the breakdown of the hemicellulose matrix and the length of fibers is decreased during the depolymerization process [12]. Compared to raw biomass or white pellets, torrefied biomass has improved flowability and fluidization behavior; these characteristics facilitate the direct injection of biomass powder into boiler furnaces [13], providing an option for achieving higher biomass co-firing ratios with minor changes to the boiler system. Therefore, torrefaction based biomass co-firing in existing coal-fired power stations has been proposed [14] and the boiler performance after 100% fuel switch has been investigated [15]. From a logistical perspective, torrefied biomass allows long-term storage without degradation and offers the possibility of utilisation of diverse feedstock sources due to the improved end fuel uniformity. The current worldwide status of torrefaction facilities has been mapped in Ref. [16]. Torrefaction is commonly combined with pelletisation, which requires further energy input requirements in terms of heat and electricity. Typically, torrefaction requires 171 kWh electricity per ton with an extra 22 kWh per ton required for pelletisation [17]; however, the same authors acknowledge that the latter figure can be significantly higher.

A handful of researchers have investigated the integration of torrefaction process in the biomass supply chain. For example, torrefied pellets can be delivered to Netherlands from Latin America at a lower cost compared to wood pellets and pyrolysis oil and can lead to lower energy cost when combined with various energy exploitation pathways [5]. Similarly, integration of torrefaction in a wood-pellet supply chain between Canada and Northwest Europe was found to lead to a 9% reduction of the feedstock delivered cost [18]. On the other hand, torrefied pellets from Mozambique to Netherlands were found to incur a higher cost than white pellets, with the cost converging in the long term [8]. The cost of supplying torrefied biomass for a pellet-fired CHP plant via train within Sweden was also examined [19]. Ultimately, there is no consensus in the literature on whether torrefaction and pelletisation of biomass in international supply chains reduces the feedstock delivered cost compared to white pellets; rather, it appears to be case specific.

All research up to now has focused on torrefaction of biomass upstream in the feedstock supply chain, close to the area of biomass collection, in order to exploit the logistical advantages of higher density during the long-distance transportation stage of the respective supply chain, usually performed by ship or train [5,8,17–21]. Torrefaction of biomass downstream in the supply chain, i.e. integrated at the biomass end-use location, has not been reported in the literature with the notable exception of [22], where biomass torrefaction at the power plant location for 10% and 20% co-firing with coal was considered, but only for domestic medium-distance supply chains in the US. Downstream torrefaction seems a rather counter-intuitive choice in principle, as the logistical advantages of increased bulk density are lost. On the other hand, there are several advantages related to the combination of downstream torrefaction with co-firing: 1) in an upstream torrefaction supply chain, biomass needs to be pelletised before being transported and then grinded at the end-use location; in downstream torrefaction both these processing stages can be avoided. This means lower investment cost in terms of equipment required, lower energy input due to avoidance of the energy-intensive pelletisation and pellet grinding stages, as well as simplification of the supply chain by removing the related processing stages. The pelletisation stage has very significant energy input requirements (1–1.2 GJ/t dry delivered), which was found to be higher in most cases than the energy required for the sea transportation stage of biomass from Latin America to Netherlands [5]; 2) in co-firing plants, use of recycled waste heat for the downstream torrefaction process can improve the overall energy efficiency, thus saving energy that in the case of upstream torrefaction would require electricity from the local grid or burning part of the biomass feedstock itself, therefore leading to self-consumption and reduced biomass availability for the end-use.

Accordingly, it can be concluded that there is a research gap in the current literature regarding (1) the feasibility of torrefaction of biomass downstream in the supply chain, at the energy conversion stage, (2) the environmental implications of such a supply chain design, (3) the effect that different co-firing rates may have on the whole supply and energy conversion system efficiency and (4) the identification of the policy conditions that would render this option feasible from a financial perspective. Therefore, the objective of this work is to examine the advantages, disadvantages and feasibility of biomass torrefaction downstream in long-distance international bioenergy supply chains from a techno-economic and carbon emissions perspective, incorporating also the biomass end-use stage. It also aims to investigate the effect that the biomass co-firing ratio may have on the whole supply and energy conversion system performance from a technical, environmental and economic aspect, adopting a whole systems approach. In particular, the case of PKS biomass originating from Malaysia is considered for co-firing in the UK, due to the commercial feedstock availability, high energy density, low moisture and easy-handling properties in its raw form, that allow long-distance transportation without requiring further pre-processing, drying or pelleting. PKS is a process residue produced in the palm oil industry from processing Fresh Fruit Bunches, and is currently an internationally traded commodity.

This work is organised as follows: Section 2 describes the system modelled and the methodology adopted in terms of modelling the biomass supply system, the torrefaction and energy conversion system processes, the system carbon emissions and the investment analysis. Section 3 presents and discusses the results regarding the