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Comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction

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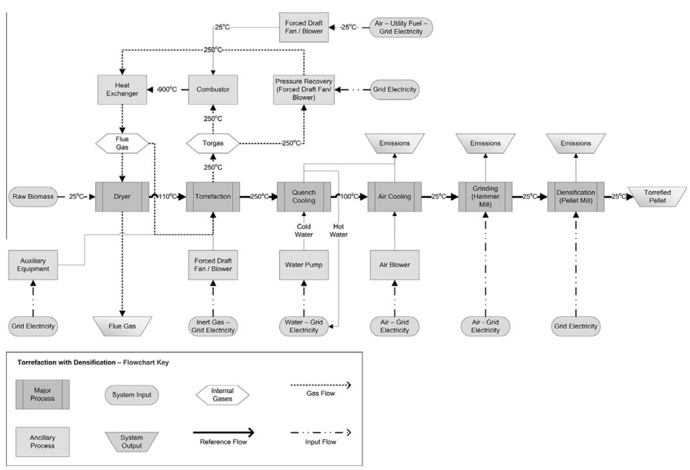
HIGHLIGHTS

- Life cycle assessment performed to assess torrefaction in wood pellet production.
- Comparative LCA of wood pellet production with and without torrefaction stage.
- Torgas recirculation allows for reduced demand for external utility fuel supply.
- Torrefied pellets offer energy and greenhouse gas savings but increase land use.
- Results are sensitive to assumptions on energy required for drying and torgas use.

GRAPHICAL ABSTRACT



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ABSTRACT

Torrefaction is a thermal pre-treatment process for upgrading raw biomass into a more energy dense fuel. Torrefied biomass is combined with a densification process to increase its bulk density similar to conventional wood-pelleting production. This paper identifies the significant environmental impacts associated with production and delivery of these two fuels, using cradle-to-gate life cycle assessment. A feedstock of Scots Pine is modelled for a localised torrefaction/wood pellet plant located in Norway, with the products from each facility delivered to a power station in the UK.

Results show that the relative benefits of torrefaction over wood-pellets are higher on per MJ delivered basis due to the higher calorific value of the fuel. The climate change and fossil depletion impacts for torrefied pellets modelled were lower than wood pellets, using an assumption that the drying requirement of the reactor was 3.0 MJ/kg water removed for both cases. Sensitivity analysis of the model indicated that the relative impact improvement of the torrefied pellet case compared to wood pellets is strongly dependent on the biomass drying requirement and the proportion of total process heat supplied by the re-circulated torrefaction gas. Land requirements for torrefied pellets are higher due to the mass losses in production.

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1. Introduction

EU countries are required to increase the use of renewable energy and reduce greenhouse gas emissions by 2020 and beyond [1,2]. Bioenergy is increasingly utilised to contribute towards these multiple policy objectives, however the local supply is often very limited due to insufficient land availability, which has led to a rapid increase in biomass imports to the EU [3]. Biomass is unique as a renewable resource, being a carbon carrier capable of storage and on-demand use making it an attractive energy source [4]. There are however several challenges associated with raw biomass which include variability, high moisture content (MC), low calorific value (CV), low bulk density, and issues around bulk handling, transportation, and logistics [5,6]. Torrefaction may address these problems to produce a more homogeneous fuel with an increased energy density and lower MC thereby improving supply chains [7–9]. It is suggested that torrefaction with densification is preferable due to improved bulk density and wider handling and transport benefits [4].

Presently wood pellets are the preferred form of biomass for transport and handling over long distances with supply rapidly increasing over the last decade [3]. Future demand for wood pellets is anticipated to continue expanding due to Government support for bioenergy in the UK and EU [6]. The environmental burdens of conventional wood pellet supply are reasonably well understood from previous research and due to biomass sustainability criteria [10–12]. In contrast there have only been limited studies which attempt to evaluate the environmental effects of torrefied wood pellets [11,13,14]. This paper addresses some of the existing research gaps by performing a life cycle assessment (LCA) of torrefied wood pellets (TP) and comparing the results with conventional wood pellet production (WP).

1.1. Characteristics of torrefaction

Torrefaction is a thermal treatment method for the conversion of biomass carried out within a relatively low temperature range of 200–300 °C, at atmospheric pressure in the absence of oxygen. This pre-treatment step destructs the fibrous structure and tenacity of biomass [7]. After torrefaction biomass exhibits hydrophobic characteristics making storage of torrefied biomass more attractive and less susceptible to biological degradation [5]. During the torrefaction process inherent moisture within the biomass is driven from the product. This drying occurs alongside a corresponding solid mass loss, achieved through the partial devolitisation of the biomass' lignocellulosic structure. The initial energy content within the lignocellulosic structure is mainly preserved in the solid product, due to only limited devolitisation in the relatively low reaction temperature range. This results in a product energy density higher than the original biomass, thus producing an energy carrier with an increased calorific value (CV). A typical mass and energy balance for woody biomass torrefaction is that 70% of the mass is retained as a solid product, containing 90% of the initial energy content [15]. The other 30% of the mass is converted into torrefaction gas (known as 'torgas'), which contains only 10% of the energy of the biomass. Torgas can be utilised as a beneficial energy source (utility fuel) in torrefaction in order to improve the overall process efficiency [9,16].

Torrefaction is able to convert biomass feedstock with non-uniform qualities into a highly homogenous bioenergy material. It assists post-production applications as a pre-conditioning process, eliminating the need for energy conversion systems to include inefficient and expensive methods to handle feedstock variability (e.g. specialist size reduction equipment required for pulverising WP in co-firing coal plants). This is crucial as issues concerning feedstock handling and transfer are often quoted as the biggest obstacles to effective conversion and use of biomass feedstock [5]. The added value compared to wood pellets includes higher co-firing percentages, cost savings in handling and transport, reduced sensitivity to degradation, and improved milling properties [4,7,8,15]. Table 1 outlines the product characteristics of torrefied woody biomass and TP compared to coal, WP and raw biomass, revealing that TP have features, like handling, milling, and transport requirements, similar to coal [8,9]. The table also demonstrates why torrefaction with densification (e.g. pelletisation) is required to realise any potential logistical advantages.

1.2. Aims and objectives of the study

The primary aim of the study is to assess the environmental impacts associated with integrating the torrefaction process into the bioenergy supply chain. This aim can be summarised as:

"Complete an environmental LCA of the torrefaction with pelletisation and wood pellet bioenergy chains on a cradle-to-gate basis with a functional unit of 1 ton or 1 MJ of TP/WP delivered".

An initial LCA was performed to evaluate the TP production process which used several modelling assumptions. A comparison of TP against the current WP technology [5] was then conducted to give context to the results of the LCA study and complete the comparative LCA between TP and WP. Specific objectives of the study were:

- Compile a detailed life cycle inventory (LCI) of the TP/WP process chains.
- Complete a cradle-to-gate LCA of the TP/WP bioenergy chains.
- Perform an impact assessment and compare the results of the TP/WP process.
- Perform sensitivity analysis to evaluate the significance of the following key modelling assumptions:
  A. Drying energy requirement to remove 1 kg water from biomass (3.0, 6.0 and 9.0 MJ/kg removed) including consideration of the CV of torgas.
  B. Post treatment grinding energy requirements of the TP process compared to the WP case.
  C. Post treatment pelleting energy requirements of the TP process compared to the WP case.
  D. Delivery requirements for increased and decreased transportation distances.

Table 1
Indicative physical properties of different biomass fuels and coal [5,8,9,17].

Parameter	Wood chips	Wood pellets (WP)	Torrefied wood	Torrefied pellets (TP)	Coal
Moisture content (MC) (wt.%)	30–50	7–10	3	1–5	10–15
Lower calorific value (CV) (MJ/kg)	9–12	15–16	19–23	20–24	23–28
Bulk density (kg/m^3)	250–300	550–700	180–300	750–850	800–850
Grindability (kW h/t)	237	237	23–78	23–78	12
Hygroscopic nature	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological degradation	Yes	Yes	No	No	No
Milling requirements	Special	Special	Classic	Classic	Classic