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Research Paper

Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment

Patricia Thornley [a,*], Paul Gilbert [a], Simon Shackley [b], Jim Hammond [b]

[a] Tyndall Centre for Climate Change Research, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, M13 9PL, UK
[b] UK Biochar Research Centre and School of Geosciences, University of Edinburgh, Crew Building, The King's Buildings, Edinburgh, EH9 3JN, UK

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ABSTRACT

Biomass can deliver significant greenhouse gas reductions in electricity, heat and transport fuel supply. However, our biomass resource is limited and should be used to deliver the most strategic and significant impacts. The relative greenhouse gas reduction merits of different bioenergy systems (for electricity, heat, chemical and biochar production) were examined on a common, scientific basis using consistent life cycle assessment methodology, scope of system and assumptions. The results show that bioenergy delivers substantial and cost-effective greenhouse gas reductions. Large scale electricity systems deliver the largest absolute reductions in greenhouse gases per unit of energy generated, while medium scale wood chip district heating boilers result in the highest level of greenhouse gas reductions per unit of harvested biomass. However, ammonia and biochar systems deliver the most cost effective carbon reductions, while biochar systems potentially deliver the highest greenhouse gas reductions per unit area of land.

The system that achieves the largest reduction in greenhouse gases per unit of energy does not also deliver the highest greenhouse gas reduction per unit of biomass. So policy mechanisms that incentivize the reductions in the carbon intensity of energy may not result in the best use of the available resource.

Life cycle assessment (LCA) is a flexible tool that can be used to answer a wide variety of different policy-relevant, LCA "questions", but it is essential that care is taken to formulate the actual question being asked and adapt the LCA methodology to suit the context and objective.

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* Corresponding author. Tel.: +44 (0) 161 3063257.
E-mail addresses: p.thornley@manchester.ac.uk (P. Thornley), p.j.gilbert@manchester.ac.uk (P. Gilbert), simon.shackley@ed.ac.uk (S. Shackley), jim.hammond@ed.ac.uk (J. Hammond).

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1. Introduction

Bioenergy is a renewable energy technology with potential to deliver greenhouse gas reductions in a number of different ways. Substantial reductions have been shown to be feasible in the power generation sector [1] and, until relatively recently increased penetration in this sector has been the main objective of UK bioenergy policy [2]. However, one of the positive attributes of biomass is that it can be used to provide a variety of different bioenergy and biomaterial products. European policy objectives [3] indicate a much wider strategic vision with biomass contributing to global greenhouse gas reductions by servicing multiple sectors, including electricity, heating and transport fuels. There is also scope for biomass to play a role in decarbonising the agricultural sector by using biochar and in production of renewable chemicals [4]. However, the amount of biomass that can be produced in any country and indeed at global scale is inherently limited by the land and material resources available and influenced by land-use competition and economic factors [5]. In recent years there has also been increasing awareness of the extent to which sustainability considerations will ultimately constrain the maximum biomass resource available [6].

It has long been recognized that it is important to make best use of limited biomass resources [7]. However, policy development, increase in biomass global trade and practical implementation has increased the importance of ensuring that appropriate, informed decisions are made based on the best available knowledge and most appropriate assessment techniques. At European level, the Renewable Electricity Directive [3] offered a high-level strategic vision of the potential of biomass, but member states have autonomy in their implementation of the directive. This requires choices between applications such as use for bioelectricity, bioheat, transport fuels, renewable chemicals and biochar production for agriculture. In order to make best use of the biomass resource these need to be informed choices, made with awareness of the differences in benefits and impacts of using biomass for different applications, as well as the trade-offs involved when one feedstock or conversion route is chosen in preference to another. Bentsen et al. [8] developed a bottom-up model that considered the most appropriate deployment of European biomass resources in line with prevailing policy objectives, but this did not take into account detailed LCA of the different biomass resources or the economic aspects of utilization. This work provides a complementary scenario-based approach that considers those aspects in depth in order to quantify the greenhouse gas related impacts and benefits of using biomass in different energy and material demand sectors. Cases have been chosen to provide a good cross-section of potential biomass applications in different sectors and at different scales with different feedstocks and are summarized in Table 1.

There have been many published life cycle assessments of bioenergy systems carried out with different scopes of system, methodologies and assumptions. This makes it extremely difficult to cross-compare and identify the relative impacts of different feedstocks, processes and end-uses. Some work has been carried out attempting to take a more holistic overview of the various LCA studies e.g. Borrion et al., carried out a meta review of LCA studies of lingo-cellulosic pathways to bio-ethanol, but found there was a strong dependency on system boundary, functional unit, data quality and allocation methods [9].

Fazi & Monti [10] evaluated different perennial cropping and annual systems but did not consider these through to delivery of the energy product to the end-user. Sterner & Fritsche [11] did consider full systems through to delivery of heat and electricity, but focused their assessment on replacing typical traditional German systems with more modern ones. They also considered the relative merits of different indicators/parameters associated with GHG reductions in comparing different bioenergy systems. The work presented in this paper provides a similarly consistent approach to cross-comparison for UK systems (where lower carbon intensity natural gas is much more dominant in the energy system, which is important as Sterner & Fritsche [11] found that GHG balances were particularly sensitive to the choice of incumbent energy provision).

This work also extends the exploration of the appropriateness of different GHG indicators in informing decisions on the best use of a limited biomass resource. Additionally it provides data relevant to current market trends of importing substantial quantities of residual biomass to the UK and Europe from overseas for large scale bioenergy production and covers a wider range of technology and product options than previously reported studies.

2. Methods

The methodology adopted for this work involved completing a full life cycle assessment for each of the systems outlined in Table 1 to establish the total global warming potential of the entire bioenergy system, including its supply chain. The greenhouse gas impacts of direct and indirect land-use change were excluded, but the consequences of displacing existing energy systems or other forms of provision were used as counterfactuals for the LCA. The functional unit chosen for

Table 1 – Systems studied.

	Feedstock	Scale	Product	Technology
1	Wood chip from UK energy crops	Small (250 kWe)	Electricity	Gasification
2	Imported forest residues	Large	Electricity	Combustion
3	Imported pellets from forest products	Small (domestic)	Heat	Combustion – individual boiler
4	Wood chip from UK energy crop	Community (100 houses)	Heat	Combustion – district heating
5	Wood chip from imported forest products	Large	Ammonia	Gasification & ammonia synthesis
6	Wood chip from UK energy crop	Medium	Biochar	Slow pyrolysis & application of char to soil

systems 1–4 was a unit of energy delivered to the end-user (in the form of electricity or heat). For the ammonia system results were calculated per unit of ammonia produced. Biochar systems have multiple outputs (energy and char) and the results explored the significance of shifting the burden of the impacts from one product to another. The detailed LCA was used to generate a number of key whole system parameters e.g. total global warming potential over system lifetime, total product output over lifetime, total harvested wood required over lifetime and total land area occupied.

A key aim of the study was to achieve a robust comparison using a consistent methodology across the different application sectors. Ideally therefore an identical feedstock would have been used for each case study. From an academic research perspective it would have been most straightforward to utilize wood chip from UK energy crops in all cases, since this is a well-studied feedstock on which we have significant amounts of life cycle research data. However, it is extremely important that life cycle assessment work aiming to inform policy decisions takes into account the reality of practical implementation. There is insufficient UK energy crop to service the demands of large scale electricity and ammonia production systems. Commercial partners indicated that a key source of biomass for large scale power generation was forest residues and so this feedstock was modeled for that case since it provided a close physical comparison to the UK energy crop but represented a more realistic implementation scenario and the input data was verified with commercial partners. There are no large scale biomass powered chemical plants with which to check commercial procurement, but imported material seemed most feasible given the scale of requirements. However, it is possible that significant proportions of bark might impact on the gasification process more than would be the case for large scale combustion and so an imported wood chip feedstock was assumed for the ammonia production case. Finally there is limited experience of producing pellets in the UK and the majority of pellets being used in heating systems are actually being imported. Therefore imported pellets were assumed for the small scale heating case. These choices gave a good balance between the aims of feedstock consistency and system realism.

A full life cycle assessment was carried out for each system. The scope of system encompassed feedstock production (ground preparation, establishment, harvesting and restoration), processing (transport, drying, storage, loading etc.) and conversion to the final product (electricity, chemical product, heat etc.). Table 2 gives more detail on the actual scope assumed for each system. Inevitably there are variations between what is included in a realistic small heating system compared to a realistic large chemical production facility, but the important feature is that there is consistency at each stage so that equivalent/comparable operations are included for each bioenergy system studied.

An economic appraisal was also completed for each system using discounted cash flow techniques. A discount rate of 5% was used to calculate the net present value of each system and this was then used as a point of comparison across the different bioenergy options by varying the value of the greenhouse gas reductions achieved to obtain identical "break-even" NPV's for the different systems i.e. the value of carbon savings that equates to zero profit for the overall system.

Table 2 – Scope of different bioenergy systems included in life cycle assessment calculations.

	Small electricity Gasification UK energy crop wood chip	Large electricity Combustion North American imported forest residues	Small heat Domestic boiler Eastern European forest product pellets	Large heat District heating UK energy crop chips	Ammonia Gasification Eastern European forest product wood chips	Biochar Slow pyrolysis SRC energy crop
Ground preparation	Pre-planting herbicide Ploughing Power harrowing			Pre-planting herbicide Ploughing Power harrowing		Pre-planting herbicide Ploughing Power harrowing
Establishment	Planting Rolling Post planting/harvesting herbicide	Forest regeneration by enrichment planting of new seedlings	Forest regeneration by enrichment planting of new seedlings	Planting (SRC Willow cuttings) Rolling Post planting/harvesting herbicide	Forest regeneration by enrichment planting of new seedlings	Planting Rolling Post planting/harvesting herbicide
Growth	First year cutback Sewage sludge application			First year cutback Sewage sludge application		First year cutback Sewage sludge application

(continued on next page)

Table 2 – (*continued*)

	Small electricity Gasification UK energy crop wood chip	Large electricity Combustion North American imported forest residues	Small heat Domestic boiler Eastern European forest product pellets	Large heat District heating UK energy crop chips	Ammonia Gasification Eastern European forest product wood chips	Biochar Slow pyrolysis SRC energy crop
Harvesting & restoration	Harvesting & chipping	Conventional forest harvesting for combined tree felling & conversion to forestry products	Conventional forest harvesting for combined tree felling & conversion to forestry products	Harvesting & chipping	Conventional forest harvesting for combined tree felling & conversion to forestry products	Harvesting & chipping
	Eradication - Glyphosate application	Collection of residues with a forwarder				Subsoiling
	Subsoiling	Extraction to forest landing site	Off-road vehicle transport to forest roadside. Truck transport (40 km roundtrip) to products processing site	Mulching/ploughing	Off-road vehicle transport to forest roadside. Truck transport (40 km roundtrip) to products processing site	Mulching
Processing, storage & provision	Tractor transport to storage area	Chipping of forest residues. at forest landing site	Chipping of small roundwood at forest products processing site	Off-road vehicle transport to storage area	Chipping of small roundwood at forest products processing site	Tractor transport to storage area
	Natural open air drying to 30% moisture content	Natural open air drying to 30% moisture content	Natural open air drying to 30% moisture content	Natural open air drying to 30% moisture content	Natural open air drying to 35% moisture content	Unloading & reclaiming of chips
		Chipping of waste wood from saw log processing				
	Unloading & reclaiming of chips at storage area	Open air drying of waste wood chips from saw log processing				
		Truck transport of waste wood chips to/from saw log processing site	Rail (170 km) transport of wood chip from forest products processing site to port-side pelletisation plant in Gdansk, Poland.	Truck transport (60 km roundtrip??) of wood chips from forest products processing site to district heating plant	Rail (170 km) transport of wood chip from forest products processing site to Gdansk, Poland. Trans-oceanic shipping (1350 km) to Felixstowe, England. Unloading of wood chips to ammonia production facility	
	Truck transport to gasification & electricity production plant	Truck transport 200 km to port for despatch	Drying, grinding & pelletising			Truck transport to biochar production plant
		Trans-oceanic shipping a round-trip distance of16,000 km from north america	Trans-oceanic shipping (1350 km) from pelletisation plant to UK and then by truck (100 km roundtrip) to domestic user			Drying of chips using heat from pyrolysis (no additional energy cost)

Biomass conversion	Drying, gasification & electricity production	Combustion in a 350 MWe FBC	Combustion of pellets in a domestic boiler	Combustion of chips in a district heating plant	Gasification of biomass in an entrained flow gasifier to produce syngas (including hammer mill and steam drying) Syngas processing to produce ammonia.	Slow pyrolysis to biochar product, syngas and bio-liquids [
Delivery of energy/chemical product		Export of electricity to national grid				Transport of biochar to suitable land Spreading of biochar on land
	Provision of electricity for use on-site	Provision of electricity for use off-site	Domestic hot water and space heating	Domestic hot water and space heating	Ammonia for use in the fertiliser industry	Incorporation of biochar into soil (discing or harrowing)
Impact of biomass product compared to reference system	Comparison to UK grid electricity	Comparison to UK grid electricity	Comparison to UK gas-fired condensing boiler	Comparison to UK oil-fired & gas-fired boilers	Comparison to conventional ammonia production using natural gas steam reforming	Comparison to fossil fuel-derived fertiliser and incorporating anticipated changes in soil emissions

The data generated from the life-cycle and economic analysis were combined to calculate a number of key parameters, significant to bioenergy development and providing a point of comparison from a policy perspective. These were:

1. Greenhouse gas emissions from the bioenergy system per unit of product.
2. Greenhouse gas savings from the bioenergy system per unit of product.
3. Greenhouse gas reductions (relative percentage) per unit of product.
4. Greenhouse gas reductions per unit of biomass utilized.
5. Greenhouse gas reductions per unit of land occupied.
6. Cost per unit of greenhouse gas reduction.

A full description of each of these parameters is given in Sections 2.1–2.6 below. All greenhouse gas parameters are expressed in “tones of carbon dioxide equivalent”, which takes into account emissions of carbon dioxide as well as methane, nitrous oxide and other key greenhouse gases.

2.1. *Greenhouse gas emissions from the bioenergy system per unit of product*

Implementing bioenergy systems often results in creation of new greenhouse gas emissions along the bioenergy supply chain. While it is often argued that these have displaced or offset other emissions that would have otherwise occurred it is, nonetheless important to minimize the new emission sources that are incurred. Fig. 1 therefore shows the total greenhouse gas emissions along the supply chain in generating a unit of electricity or heat.

Equivalent figures were obtained for the ammonia and biochar systems but they do not provide an instructive comparison since the functional unit of comparison is different. For information these were 613 kg CO_2/t ammonia produced and 306 kg CO_2/t biochar produced.

2.2. *Greenhouse gas savings from the bioenergy system per unit of product*

Pursuit of greenhouse gas reductions demands consideration of the incumbent system that is being displaced and so Fig. 2

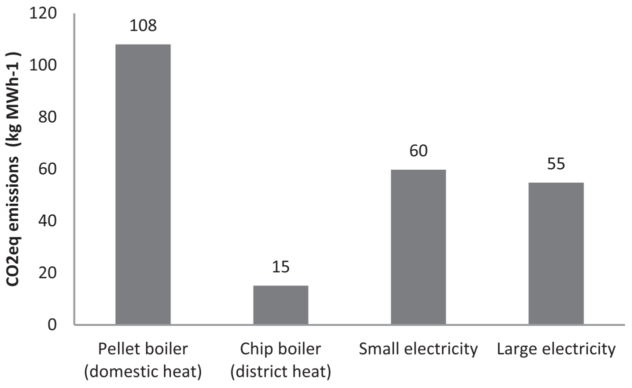

Fig. 1 – Greenhouse gas emissions across the supply chain per unit of energy delivered for the different bioenergy systems evaluated.

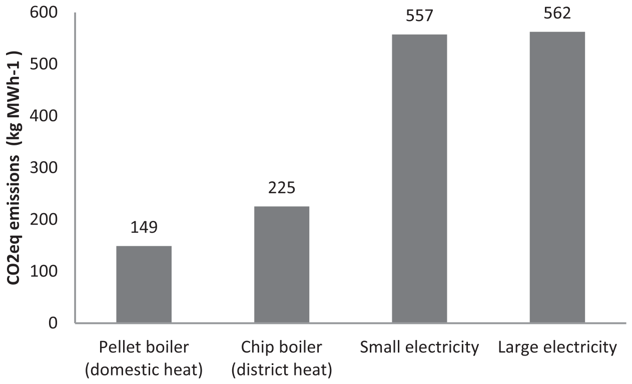

Fig. 2 – Absolute greenhouse gas savings per unit of energy delivered.

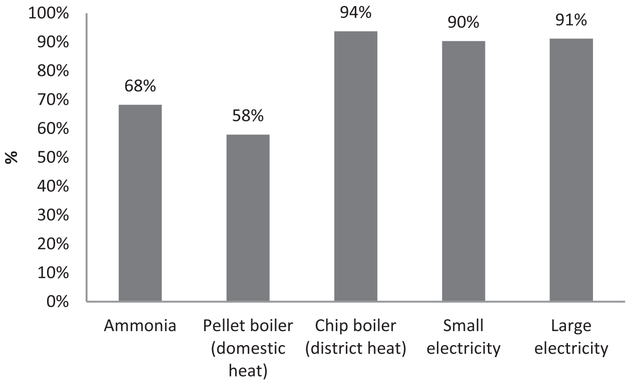

Fig. 3 – Relative greenhouse gas reductions compared to the reference case.

presents the absolute results for greenhouse gas reductions when the bioenergy system is considered compared to a specified reference system. The reference systems used for electricity are; the UK grid average figures across all its generation capacity; a natural gas fired condensing domestic boiler and a natural gas fired district heating system. As for Fig. 1 these figures are presented for the systems with energy products only as it does not make sense to compare across different functional units. The ammonia system achieved CO_2 savings of 1317 kgt^{-1} while the biochar system was 2264 $kg\,t^{-1}$.

2.3. Greenhouse gas reductions (relative percentage) per unit of product

The UK's commitments under its Climate Change Act specify an 80% reduction in greenhouse gas emissions by 2050 compared to 1990 levels. While it is not essential (or even desirable) that this percentage reduction will be achieved equally in all demand sectors, it is the case that if reductions in one sector are less than 80%, other sectors will have to exceed the target in order to compensate. Similarly, if a particular sector is to achieve an 80% reduction and bioenergy implementation will not reach that level, then other technologies that reach a higher level of reduction will have to be used in tandem. Therefore, it is relevant to examine the percentage reduction that different bioenergy systems can achieve from typical existing base cases, as shown in Fig. 3. This information can guide where to target biomass resources most effectively when considered alongside other low carbon technologies to achieve commitments and the extent to which bioenergy can meet a sector target or the extent to which it must be supported by other technologies. It is worth noting in this context that the UK government is currently consulting on legislation to "cap" the contribution different biomass technologies can make to renewable energy targets. Fig. 3 presents these figures for all of the bioenergy systems except biochar. This provides the cross-sectoral comparison required, but biochar is excluded since it is the only system to deliver multiple products; some of which do not have a ready reference comparison.

2.4. Greenhouse gas reductions per unit of biomass utilized

There is only a limited amount of biomass available and it is often argued that therefore it should be used in the most efficient way possible. Fig. 4 therefore presents the greenhouse gas reductions achievable by a unit of biomass for each of the applications studied. The unit of comparison is an oven dry tonne of biomass at point of harvest. Therefore it takes into account all processing losses, application inefficiencies etc. This is important as different levels of processing, degradation and losses will be incurred for the input feedstock specification associated with different systems/applications and this needs to be taken into account in a whole system assessment.

2.5. Greenhouse gas reductions per unit of land occupied

There are increasing concerns about the competition between food and fuel and awareness of the environmental, social and economic implications of land-use for bioenergy [12]. The figures presented in Fig. 5 therefore give the "land efficiency" of carbon reductions achieved using different biomass systems: "greenhouse gas reductions per unit of land occupied". In order to give a fair comparison between land occupancy for different lengths of time the units used for this comparison

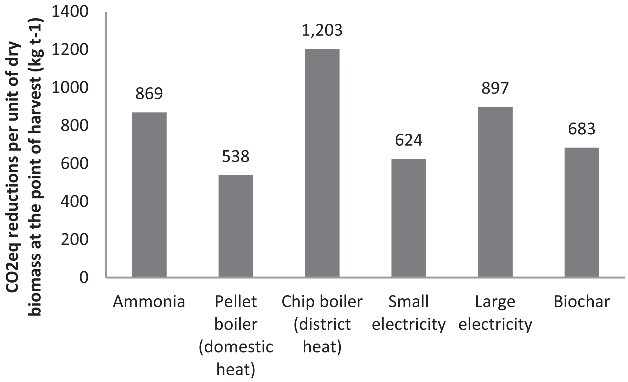

Fig. 4 – Greenhouse gas reductions per unit of biomass.

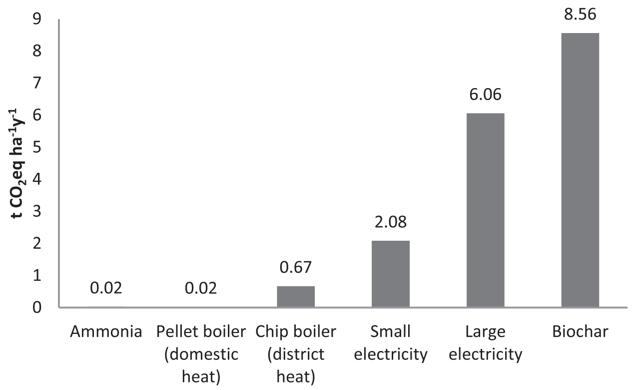

Fig. 5 – Greenhouse gas reductions per unit of land occupied.

are greenhouse gas reductions per hectare per annum. This parameter is significantly dependent on the type of biomass used for each system and the conversion efficiencies of the processes.

2.6. *Cost per unit of greenhouse gas reduction*

While addressing climate change by reducing greenhouse gas emissions is a major challenge facing society there is substantial concern about the cost of doing so. The Stern report [13] quantified the cost of addressing climate change and of not addressing it and presented a convincing case that the overall costs were justifiable. However, there is no doubt that some technologies are more cost effective than others at delivering greenhouse gas reductions. This may be a function of technology maturity with costs expected to decrease in future and so national governments often provide policy support that recognizes the different costs associated with implementing different technologies [14,15]. This is intended to provide market support to those technologies where there is a market failure due to technological immaturity and which therefore most need it and ensure some diversity in the deployment of renewable energy so that one option does not become dominant. However, even within the bioenergy sector there are variations in the cost effectiveness of the carbon reductions delivered by the different technology options available. Therefore, it is appropriate to consider a measure of carbon abatement cost effectiveness. In this work a discounted cash flow analysis has been carried out over an 18 year period that allows calculation of the net present value of the bioenergy system. The life cycle assessment work has been used to calculate the total greenhouse gas reductions delivered over the same plant lifetime. A figure was then assumed for the monetary value per unit of carbon reductions (£/t carbon saved). This figure was then varied in the analysis to achieve a net present value of zero for the bioenergy system. A net present value of 0 is effectively a "break-even" commercial system with no positive rate of return to attract investors, so no incentive for its implementation. This is therefore the ***minimum*** value of carbon price that would be needed to facilitate introduction of the technology in the commercial market place. In reality such a price would be insufficient to trigger investment, but it provides a point of comparison in terms of which bioenergy systems require a higher or lower value of carbon price in order to trigger implementation. It is worth noting that, given the highly volatile status of existing carbon markets, it is unlikely that biomass development will be accelerated by changes in carbon prices alone. However, the calculation still provides a measure of the cost effectiveness of the greenhouse gas reductions achieved through different biomass technologies. The discount rate used in the calculations is relatively low (5%), but this reflects the current (as of 2014) economic climate across much of Europe and seems to provide a reasonable assumption at least for the medium term. The results of this analysis are shown in Fig. 6.

3. Results and discussion

The results obtained following the above methodology are outlined in Figs. 1–6, with brief commentary highlighting the main points, which are then used to draw more general conclusions in Section 4. Figures were calculated for all parameters for all bioenergy systems but those presented here are those that can be meaningfully compared e.g. it is not instructive to compare the greenhouse gas emissions associated with production of a unit of biochar with those for a unit of heat and so only the systems that deliver energy end products are considered for parameters 1–4. However, it is logical to compare the carbon reductions achievable by using a unit of biomass in the heating sector with those achievable in the chemicals sector and so for parameters 5 and 6 all 6 different bioenergy uses are considered.

Fig. 1 clearly shows that the pellet boiler system results in the largest greenhouse gas burden along the supply chain; higher even than the two electricity systems studied. The wood chip district heating boiler has a very substantially lower level of supply chain emissions than any of the other technologies. The high degree of processing required for pellet production drives the high level of supply chain emissions; while the transport and handling regime results in both the electricity systems having intermediate emission levels. The higher efficiency of the larger electricity plant effectively offsets the additional greenhouse gas emission incurred with bringing the large quantity of feedstock to a central point for conversion.

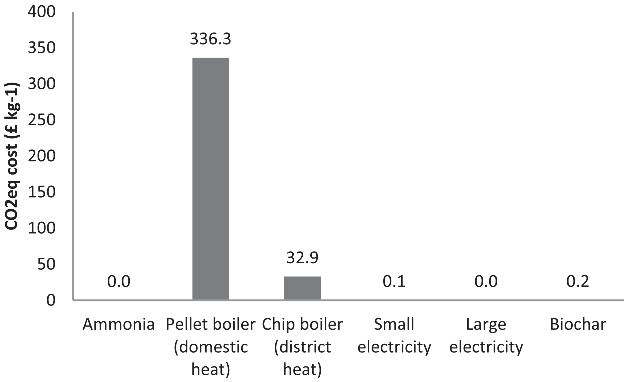

Fig. 6 – Cost per unit of greenhouse gases saved.

Both of the electricity systems give very much higher greenhouse gas savings than the heating ones. This is primarily driven by the relatively high carbon intensity of the reference case for the UK, since there is large scale dependence on fossil-fuel powered generation, with both coal and gas fired plant making a significant contribution. Renewables penetration is very low in the electricity sector but domestic heating is compared to a highly efficiency natural gas boiler. These dominate the domestic energy sector because of the readily available and historically low cost natural gas and specific government initiatives to encourage high efficiency condensing boilers. Therefore the benefits to be gained from using biomass to displace electricity rather than heat are much greater.

The district heating system gives the highest percentage reduction of greenhouse gases compared to the reference system. It should be noted that this is compared to a reference system of natural gas district heating and so is not driven by the efficiency or performance of the district heating system itself, but only by the switch to biomass fuel. The main driver appears to be the ability to use a relatively unprocessed fuel (compared to e.g. the pellet fired system) combined with the relatively small scale of activity (transportation impacts are more visible with the larger scale ammonia and electricity systems). The ammonia figures may also be particularly influenced by the fact that the efficiency of ammonia production plants has improved substantially in the last 20 years and the counterfactual is based on a relatively low carbon intensity natural gas feedstock. Therefore further reductions are now more difficult to achieve as the baseline comparison is already quite carbon efficient.

Fig. 4 shows the greenhouse gas reductions per unit of biomass utilized. The wood chip boiler for district heating clearly delivers the greatest greenhouse gas reduction impact per unit of biomass. This is followed by the ammonia and large electricity systems; with biochar and small electricity at a similar level and the pellet boiler last. The order seems to correlate with the extent to which the fuel is assumed to be pre-processed prior to the point of conversion.

The results presented in Fig. 5 are driven by a combination of process efficiency, carbon intensity of the displaced product and the efficiency of biomass production. Therefore the systems with high biomass yields tend to perform better than those with lower yields. At the point of sale a unit of wood produced from a short rotation coppice system may appear identical to a unit of wood produced by a forestry systems; however their land use requirements are quite different. The yield assumed for forestry systems in this work is relatively low, since it was assumed that bioenergy applications would only be able to access a small proportion of the wood produced from a commercial forestry system and so the land area assumed for the calculations is producing more than just the bioenergy material. This is what drives the relatively low results for the ammonia and pellet boiler systems. This could be considered “unreasonable” as it is not taking account of co-products with appropriate allocation procedures. However, it is a sensible approach to take if what we are concerned about is the total amount of reductions that bioenergy systems are ever going to be able to deliver since the absolute land constraint is the finite area available for forestry, not the proportion of that area that should properly be attributed to biomass. In other words it would be misguided to allocate only a proportion of the land to the bioenergy system when the ultimate constraint is not the bioenergy proportion but the total amount of land on our planet that might be under harvestable forest cover at any point in time.

Fig. 6 shows that the heating systems, particularly the pellet boiler, have very high costs per unit of greenhouse gas savings, while the electricity, biochar and ammonia systems all have much lower carbon costs. In fact the ammonia system does not require any value to be placed on the carbon reductions at all – it could be commercially implemented today on a simple investment cost basis, but there are substantial commercial risks associated with deployment which impede that [4]. It is interesting to note that when heating and electricity cross-comparisons have been carried out in other European countries they often result in more favorable outcomes for heating systems. However, the heating load for the UK climate is characterized by a relatively low overall load factor and a high disparity between peak loads in summer and winter. This results in relatively high capital expenditure to install a system that is capable of delivering relatively modest overall annual output. Additionally a key driver for the heating systems requiring a higher cost of carbon appears to be that the market value of heat compared to electricity or the chemical or fertilizer products is very low. Finally the heating counterfactual assumed is a highly efficient natural gas boiler. These are dominant within the UK domestic heating sector and so make a sensible choice, but they also have a relatively low carbon intensity compared to other heating options and so the benefit of replacing them with biomass is more limited than it may be in other contexts.

4. Conclusions

The results presented in this paper illustrate the importance of fully understanding the climate mitigation policy objective when considering how to make the best use of bioenergy. Biomass can be used for many different purposes and the benefits of doing so vary substantially from one system to another. So under a particular set of economic circumstances pertaining in the UK (before any subsidy, incentive or support is taken into account) ammonia production can provide the most cost effective greenhouse gas reductions; while biochar production from energy crops makes best use of land and district heating systems result in the highest level of greenhouse gas reductions per unit of biomass utilized. Nevertheless the normal focus of climate policy is on relative greenhouse gas reductions compared to the incumbent system and here district heating, small and large scale electricity all perform very well. However, consideration of the absolute emission reductions actually achieved by different technologies favors electricity deployment rather than heat; while appreciation of the cumulative impacts of greenhouse gas emissions suggests that annual greenhouse gas “budgets” are a more appropriate approach, placing more focus on the actual emissions than the savings.

The results also illustrate the importance of appropriate framing of the research question when carrying out life cycle assessment. Life cycle assessment is a very flexible tool, which can be adapted to address a wide variety of different research questions. Policy mechanisms have been put in place at European and national level which use different LCA calculator tools to support particular parts of the policy agenda. These can provide useful cross-comparisons for different types of systems but it is critically important that LCA for research (particularly policy relevant research) is appropriately carried out by considering the actual nature of the research question and adapting the LCA methodology to suit. This includes careful consideration of the most appropriate metrics to compare the relative merits of different bioenergy systems. As this work has shown the same systems can score very differently against different framings of a simple "greenhouse gas reduction" metric and it is critical that the implications of this are understood by researchers and policy-makers.

Clearly bioenergy systems can make a contribution to climate mitigation but making the best use of the limited biomass resource requires careful consideration of what greenhouse gas reductions are actually required, how bioenergy deployment interfaces with other climate mitigation options and how a particular resource can best be targeted.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.05.002.

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