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Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting: A bioenergy case study

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A R T I C L E I N F O

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A B S T R A C T

In order to avoid dangerous climate change greenhouse gas accounting methods are needed to inform decisions on mitigation action. This paper explores the differences between 'attributional' and 'consequential' greenhouse gas accounting methods, focusing on attributional corporate greenhouse gas inventories, consequential life cycle assessment, and project/policy greenhouse gas accounting. The case study of a 6 MW bioheat plant is used to explore the different results and information these methods provide. The findings show that attributional corporate inventories may not capture the full consequences of the decision in question, even with full scope 3 reporting – and are therefore not sufficient for mitigation planning. Although consequential life cycle assessment and the project/policy level method both aim to show the full consequences of the decision, the project/policy level method has a number of advantages, including the provision of a transparent baseline scenario and the distribution of emissions/removals over time. The temporal distribution of emissions/removals is important as the carbon debt of the bioheat plant can exceed 100 years, making the intervention incompatible with 2050 reduction targets. An additional contribution from the study is the use of normative decision theory to further develop the idea that the uncertainty associated with bioenergy outcomes is itself a highly decision-relevant finding.

1. Introduction

Climate change poses serious global risks (Stern, 2006), and greenhouse gas accounting methods are needed to understand the scale of emissions associated with different activities, and to assess the effectiveness of climate change mitigation options. A large number of different greenhouse gas accounting methods have been developed, including national inventories (IPCC, 2006), community/city inventories (Schultz et al., 2014; British Standards Institute, 2013), policy assessments (WRI, 2014), corporate/organisational inventories (WBCSD/WRI, 2004; WBCSD/WRI, 2011a; ISO, 2006b; Pelletier et al., 2013), project-level methods (WBCSD/WRI, 2005; ISO, 2006c), and product-level life cycle assessment (British Standards Institute, 2012; ISO, 2013; ISO, 2006a; WBCSD/WRI, 2011b; European Commission, 2013), among others. Given this array of different methods it is not always clear which method(s) are the most appropriate for a given purpose.

A helpful distinction between types of method, which has developed specifically within the field of life cycle assessment (LCA), is that between what are called 'attributional' and 'consequential' approaches (Finnveden et al., 2009; Weidema, 2003; Ekvall and Weidema, 2004; Plevin et al., 2014b). Attributional methods can be broadly defined as inventories of anthropogenic emissions and removals for a given inventory boundary, while consequential methods aim to quantify the total change in emissions that occur as a result of a given decision or action (Brander and Ascui, 2015; Brander, 2015b). The LCA literature suggests that consequential methods are more appropriate for decision-making on mitigation actions as they capture the total consequences of the decision at hand (Weidema, 1993; Plevin et al., 2014a, 2014b), and empirical studies show that basing decisions on attributional LCA can result in mitigation actions which unintentionally increase rather than decrease emissions (Searchinger et al., 2008; Hertel et al., 2010).

Previous research has suggested that the attributional-consequential distinction can be extended beyond the field of life cycle assessment to create a generic categorical scheme for

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classifying all forms of physical greenhouse gas accounting (Brander and Wylie, 2011; Brander, 2015b; Brander and Ascui, 2015). Brander, (2015b) suggests that corporate/organisational inventories (henceforth, referred to as corporate inventories), national inventories, and community inventories, can be categorised as being *attributional* in nature, while project-level and policy-level methods are *consequential* in nature. One benefit from developing this categorical scheme is to allow inferences about the appropriate use of methods of a certain categorical type, e.g. if corporate GHG inventories are attributional in nature it can be inferred, based on the conceptual analysis and empirical evidence from the field of life cycle assessment, that they are not sufficient for informing climate change mitigation decisions (Brander and Ascui, 2015). A further benefit from developing the attributional-consequential distinction as a broader categorical scheme is to facilitate the exchange of methodological lessons between approaches of the same categorical type (Brander, 2015b).

Although it can be inferred that corporate inventories are not appropriate for informing mitigation decisions, based on the way attributional inventories do not necessarily capture the total consequences of a decision, it is also useful to provide an empirical illustration in order to demonstrate what might otherwise be regarded as a largely theoretical issue. Such an empirical demonstration appears to be needed for a number of reasons: firstly, the existing guidance (WBCSD/WRI, 2004; WBCSD/WRI, 2011a; ISO, 2006b), literature (Downie and Stubbs, 2013), and government policies (Defra, 2013; UK Government, 2013; Scottish Government, 2015; Pelletier et al., 2013) regarding corporate inventories are not sufficiently clear on the limitations of the information provided; real-world organisations, such as the organisation studied in the present paper have mistakenly used their corporate inventories for mitigation decision-making; and thirdly, although empirical evidence on the magnitude of difference between attributional and consequential approaches exists within the field of life cycle assessment (e.g. Searchinger et al. (2008)), an equivalent empirical illustration is not yet available for corporate GHG inventories. The present study also seeks to illustrate the possibilities opened up by the attributional-consequential categorical scheme by demonstrating the methodological lessons that can be identified and transposed between different forms of consequential method, i.e. between consequential LCA and project/policy assessment. Again, although these lessons have been explored conceptually in previous research (Brander, 2015b), the significance of the differences between the methods has not yet been demonstrated empirically.

In addition to contributing to the conceptualisation and development of different greenhouse gas accounting methods, the study also directly contributes to the extensive debate on the greenhouse gas impacts of bioenergy (Bernier and Paré, 2013; Bright et al., 2012; Schulze et al., 2012; Edrisi and Abhilash, 2015; Searchinger, 2012; Haberl et al., 2012; Upham and Smith, 2014; Cherubini et al., 2009; Favero and Mendelsohn, 2013; Haberl et al., 2013). This debate is a highly topical one, given the considerable corporate and governmental support for bioenergy as a climate change mitigation option (e.g. Diageo (2015); European Parliament and Council of the European Union (2009); UK Government (2012); US Department of Energy (2015)). The existing literature on bioenergy shows a wide range of possible outcomes (i.e. ranging between large reductions to large increases in net emissions), and the present study applies normative decision theory to further develop the idea that such uncertainty is a highly decision-relevant finding in its own right (Plevin et al., 2014b).

2. Method

The overall approach used in this study is to apply a corporate inventory method, a consequential LCA, and a project/policy-level assessment to the same case study decision scenario, and then to undertake a comparative analysis of the results from each method. The decision to develop a bioheat plant was selected for the case study as data were available for a proposed 6 MW bioheat plant in the east of Scotland, and bioheat was considered likely to provide a 'crucial' case (Gerring, 2004), i.e. one which illustrates the differences between the methods. A single case study will not allow the estimation of the likelihood that attributional corporate inventories omit important consequences, but it is sufficient for inferring that for any given decision scenario it is uncertain whether using a corporate inventory is sufficient. The long timeframe for the growth of woody biomass was also expected to illustrate the difference in the treatment of the temporal distribution of emissions/removals between the consequential LCA and the project/policy method. A further reason for selecting a bioenergy case study is that bioenergy is a highly topical issue, given the high level of policy support, noted above. Each of the greenhouse gas accounting methods applied to the case study decision scenario are now described in turn.

The GHG Protocol's *Corporate Accounting and Reporting Standard* (WBCSD/WRI, 2004) was used for undertaking the corporate inventory, as this is considered the most widely used standard for such inventories (Green, 2010). ISO 14064-1:2006 *Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and remova*ls would have yielded very similar results, although the GHG Protocol requires the quantification and reporting of CO_2 emissions from biomass, whereas for the ISO standard this is recommended but optional. The organisational boundary for the inventory is the organisation commissioning the bioheat plant, and the operational boundary is all emissions from energy use at facilities owned/operated by the organisation (termed 'scope 1' emissions); all emissions from purchased electricity, heating or cooling ('scope 2' emissions); and all other value-chain sources for which data were available ('scope 3' emissions); and emissions from the combustion of biomass and biofuels (reported separately from the scopes). The operational boundary is shown in detail in Table 1.

Activity data were collected from the energy officer at the organisation commissioning the bioheat plant for the period August 2012 to July 2013. Emission factors were sourced from the Department for the Environment, Food and Rural Affairs and the Department for Energy and Climate Change (Defra/DECC, 2015). However, the Defra/DECC emission factors are provided in units of CO_2e using global warming potentials (GWPs) from the Second Assessment Report (SAR) (IPCC, 1996), whereas the GHG Protocol *Corporate Standard* requires reporting in tonnes of each greenhouse gas, and CO_2e should be calculated using the latest available 100 year global warming potentials. The published factors for CH_4 and N_2O emissions were therefore divided by the SAR GWPs to allow

Table 1
Operational boundary.

Scope	Emission source
Scope 1	Natural gas
	Diesel
	Biodiesel
	Petrol
Scope 2	UK grid electricity
Scope 3	Purchased goods and services
	Capital goods
	Fuel and energy related activities
	Waste generated in operations
	Business travel
Biogenic emissions	Biofuel component of biodiesel
	Woody biomass

reporting in tonnes of CH_4 and tonnes of N_2O, and these figures were then multiplied by the Fifth Assessment Report GWPs (IPCC, 2013).

The corporate inventory was then used to assess the benefits of developing the 6 MW bioheat plant by comparing two alternative versions of the inventory: the inventory with the bioheat plant; and the inventory with the continued use of natural gas. It is important to note that the GHG Protocol *Corporate Standard* and ISO 14064-1 do not provide guidance on how to use greenhouse gas inventories to select mitigation actions, however, they do suggest that such inventories can be used to manage emissions. In addition, the organisation commissioning the bioheat plant used its own corporate inventory data to support its decision (i.e. corporate inventories are used in this way in practice). The level of guidance provided on the use of attributional inventories to inform decision-making is discussed further in the Discussion section (4.1).

The upstream or embodied emissions associated with the bioheat plant (the boiler, pipes, and installation activities etc.) were estimated using projected capital expenditure figures from the design team and the input-output supply chain emission factor for construction from Defra/DECC (2012). The resulting emissions estimate should be viewed as indicative only, as the factor is based on average emissions across the construction sector in the UK. The upstream emissions from the cultivation and processing of woody biomass were estimated using figures for the expected energy input to the bioheat plant and Defra/DECC's (2015) emission factor for upstream emissions from wood chips (0.01662 $kgCO_2e$/kWh of woodchips). These emissions were included as part of the scope 3 ‘fuel and energy-related activities (not included in scope 1 or 2)’ category, while the CO_2 emissions from the combustion of the biomass itself are reported separately from scopes 1, 2, and 3, as per the requirements of the *Corporate Standard* (WBCSD/WRI, 2004, p.63).

Turning to the comparator consequential methods, a consequential LCA and a combined project/policy-level assessment were undertaken (the project and policy-level methods were combined as previous research suggests that these methods have essentially the same structure and approach (Brander, 2015b)).

Taking the consequential LCA first, it is important to note that consequential LCA is not a clearly standardised method, and a number of different approaches and interpretations are evident in the literature (Zamagni et al., 2012). In the absence of a recognised standard for consequential LCA, the approach used in the present study was to follow the guidance provided in Ekvall and Weidema (2004), and Weidema et al. (2009), with the general structure for the consequential LCA taken from the *International Reference Life Cycle Data System Handbook* (European Commission et al., 2010). Some commentators (e.g. Plevin et al. (2014b) have more recently used the label ‘consequential LCA’ to refer to a methodological approach much closer to the project/policy method described below, and an alternative framing for the comparative analysis in this paper could possibly be between ‘traditional’ and ‘recent’ interpretations of consequential LCA. However, for clarity, the labels used for the methods compared in the present study are ‘consequential LCA’ and the ‘project/policy’ method. Following the consequential LCA guidance listed above, the goal and scope of the study is to estimate the change in greenhouse gas emissions/removals caused by the decision to implement a 6 MW bioheat plant in the east of Scotland, with a 200 year assessment period. The functional unit is 1 kWh of delivered heat.

For the life cycle inventory stage, the processes included are those that change as a result of the decision, i.e. the marginal processes (Schmidt and Weidema, 2008). It is worth noting that the requirement to identify all the processes that change is the same in the project/policy method, though there are differences in the structure of the methods which are discussed later. In consequential LCA, changes caused by the supply of co-products, or other instances of multi-functionality, are addressed through the technique ‘substitution’ (also sometimes referred to as ‘system expansion’). Substitution involves identifying the product systems that are displaced (i.e. *changed*) by the production of co-products, and crediting the displacement of those product systems to the decision studied, as the avoidance of those systems and their associated impacts are assumed to be a consequence of the decision (Weidema et al., 2009).

Similarly, if the decision in question causes the use of a constrained resource that would otherwise be used for an alternative purpose, then the substitute processes used to fulfil that purpose are included in the life cycle inventory, as they are affected by the decision in question (Ekvall and Weidema, 2004, p.167). In the case of the present study, an example of a constrained resource is saw mill residues, the use of which for bioenergy entails that fewer residues are available for the production of medium density fibre (MDF) board, and the reduced production of MDF may be replaced by plasterboard, as a substitute. The production and other life cycle stages of *plasterboard* are therefore included in the inventory as they *change* as a result of the decision studied.

Finally, one-off emissions, such as those from the construction of the bioheat plant, were amortised over the 25 year lifetime of the plant (and the need for an amortisation period in consequential LCA is explored in the Discussion (4.2), as amortisation is absent in the project/policy method). The remaining methodological details of the consequential LCA, e.g. scenario modelling, data, emission factors etc., are shared with the project/policy method and are therefore described in conjunction, following a brief overview of the features unique to the project/policy approach.

The guidance and standards used for implementing the project/policy method are *ISO 14064-2* (ISO, 2006c), the *GHG Protocol for Project Accounting* (WBCSD/WRI, 2005), and the GHG Protocol's *Policy and Action Standard* (WRI, 2014). The fundamental structure of this approach is to create a time-series of emissions/removals for a baseline scenario, i.e. the scenario in which the decision has not been taken, and for a ‘with decision’ scenario. As with consequential LCA, the intention is to include all the emission source/sinks that *change*. Subtracting the baseline emissions/removals from the decision scenario emissions/removals provides the change in emissions/removals caused by the decision. This methodological structure is illustrated in Fig. 1 below, with the total change in emissions indicated by the shaded area.

Other than these structural differences the methodological details of the two consequential methods are largely the same. The same data, scenarios, assumptions, and emission factors were used

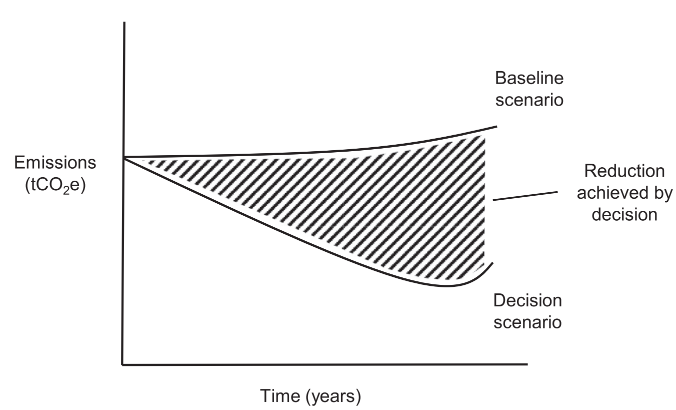

Fig. 1. Illustration of the key components of the project/policy accounting method.

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for both methods (with the exception of the emission factors for transportation and UK grid electricity, which are expected to reduce over time, and this dynamic element is accommodated in the project/policy method's time-series structure, but not included in the consequential LCA). Details of the input data, assumptions, forest carbon model, and emission factors are provided in the online supporting material.

A highly important and shared feature of the consequential methods is the use of scenarios for modelling the different possible marginal systems affected by the decision in question (Weidema et al., 2009; WRI, 2014). Seven scenarios, and thirteen sub-scenarios were modelled, and are summarised in Table 2 below.

The selection of scenarios was informed by number of principles and heuristics from the consequential LCA guidance, e.g. the marginal processes must be unconstrained; are likely to be the least-cost form of production in a growing market; and markets are assumed to be linked unless there is evidence to the contrary (Ekvall and Weidema, 2004; Weidema et al., 2009). The selection of scenarios was also based on a range of information: published studies (e.g. Lamers et al. (2015) and Lauri et al. (2014) indicate that the marginal supply will come from increased overseas production); interviews (e.g. information from the commissioning organisation and local forest managers suggested increased local production as a possible marginal system); industry reports (e.g. the Wood Panel Industries Federation (2010) suggests the marginal effect will be material displacement and substitution); and government greenhouse gas accounting tools (e.g. DECC's *Biomass Emissions and Counterfactual Model* (2014) includes both overseas production and material substitution effects).

An assessment of the probability of each of the scenarios has not been undertaken in the present study, though all of the scenarios modelled are considered to be plausible. It should be noted that the actual change caused by the decision may involve combinations of these scenarios/marginal systems, and therefore the presentation of individual scenarios is a simplification of a more complex reality. Furthermore, the scenarios modelled are not exhaustive, and alternative scenarios are also possible. The scenarios are best viewed as selective ‘illustrative examples’, following the approach in Zanchi et al. (2012, p.762).

An attempt was made to include all significant emission sources/sinks affected in each scenario, e.g. above ground biomass, soil carbon, whole-of-life emissions for all energy and material inputs etc. However, the ‘chain of consequences that can be analysed does not seem to have an end’ (Zamagni et al., 2012, p.913), and alternative modelling methods could be used to include additional cause-effect pathways not present in this paper. For instance, general equilibrium modelling could be used to capture the effects of changes in income caused by the decision (e.g. Smeets et al.

Table 2
Details of scenarios for the marginal systems affected by the decision (used in the consequential modelling).

Name of scenario	Description	Name of sub-scenario	Description
1. Overseas production	Increase in demand for wood chips increases the production at the world marginal supplier of biomass. Supply in the UK is constrained and so the marginal supply is overseas production.	1.1. Sustainable forest management	The harvested forest is replanted.
		1.2. Unsustainable forest management	The harvested forest is not replanted.
2. Local production	Increase in demand for wood chips is met from local wood resources that would otherwise not be harvested/utilised, e.g. harvesting of shelter belts, small farm woodlands, wooded steep-sided gullies.	2.1. Local production without co-products	Whole trees are harvested and used for wood chips.
		2.2. Local production with co-products	Part of the tree is used for wood chips and the remainder is used for pallets and construction. In order to make the transportation of the co-products to the saw mill economically viable the trucks backhaul biomass to the bioheat plant.
3. Thinnings	Increase in demand for wood chips makes increased thinning of existing productive forestry economically viable.	3.1. Without co-products	There is no change to the proportion of harvested stem wood that can be used for pallets and saw logs.
		3.2. With co-products (marginal saw log displacement)	Thinning changes the proportion of harvested stem wood that can be used for pallets and saw logs. Reduction in plastic pallet production and marginal saw log production.
		3.3. With co-products (cement render displacement)	Thinning changes the proportion of harvested stem wood that can be used for pallets and saw logs. Reduction in plastic pallet production and use of cement render.
4. Fencing	Increase in demand for wood chips displaces the use of wood for fence posts and increases the production of concrete posts.	4.1. End of life combustion	The wooden posts would have been combusted for energy at their end of life.
		4.2. End of life decay	The wooden posts would have decayed aerobically at their end of life.
5. Pallets	Increase in demand for wood chips displaces the use of wood for pallets and increases the production of plastic pallets.		The reduced demand for wooden pallets due to the longer lifetime of plastic plastics increases biomass availability and displaces natural gas combustion.
6. MDF	Increase in demand for wood chips increases biomass market demand for wood fibre and reduces production of medium density fibreboard (MDF), and increases the production of plasterboard.		
7. Particle board	Increase in demand for wood chips increases biomass market demand for wood fibre and reduces the production of particleboard, and increases the production of breeze blocks.	7.1. Breeze block lower estimate	A lower emission factor for breeze blocks is used (Hammond and Jones, 2008).
		7.2. Breeze block upper estimate	A higher emission factor for breeze blocks is used (DECC, 2014).

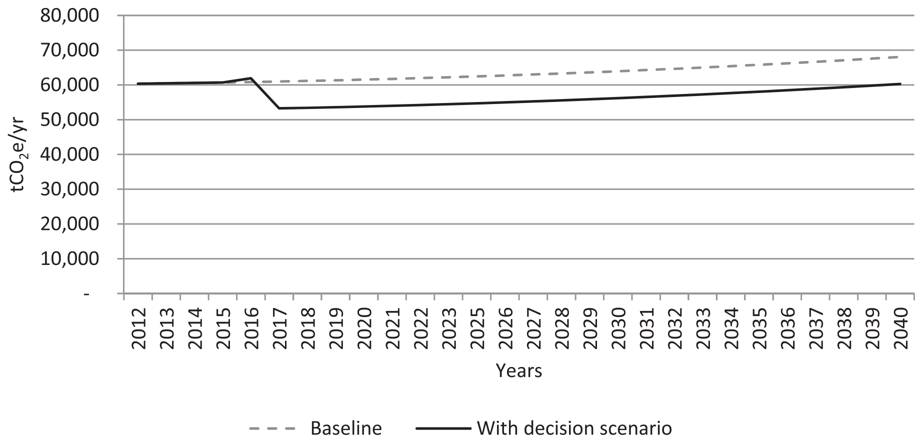

Fig. 2. Corporate GHG inventory – scopes 1, 2 and 3.

(2014), and agent-based modelling could be used to include behavioural effects from peer-learning (e.g. Alexander et al. (2013)). Causal chain maps were produced to provide an overview of the marginal processes and emission sources/sinks included in each scenario, and are presented in the online supporting material. The conjunction of the causal chain maps and the list of data, assumptions, forest growth model, and emission factors provides information for replicating the findings. However, it is worth providing a brief explanation of two of the more complicated scenarios: increased overseas production (scenario 1); and increased local production (scenario 2).

Increased overseas production (scenario 1) does not necessarily entail that the biomass combusted at the 6 MW bioheat plant is from overseas, but rather that this is the marginal effect of an increase in demand for woody biomass. It is assumed that the consumers/producers who would have otherwise used the biomass combusted in the bioheat plant will seek an alternative source of biomass, creating a causal chain which ultimately causes an increase in production overseas. There is considerable evidence to suggest that this is a likely scenario: UK demand for biomass is expected to exceed domestic supply (John Clegg Consulting Ltd, 2006); UK forest production is expected to decline from 2030 onwards (Forestry Commission, 2014); biomass is already an internationally traded commodity (FAO, 2009; Lamers et al., 2015; Buongiorno et al., 2010), suggesting there is no market delimitation due to trade or geographical barriers (Weidema et al., 2009); and the international marginal supply of biomass is projected to come from the US, South America, Africa, and Asia, with only limited additional supply within Europe (Lauri et al., 2014).

An alternative possible scenario is that the increase in demand for biomass brings otherwise unmanaged local woodland, such as shelter belts and wooded gullies, into production (scenario 2). Subscenario 2.2 models the possibility that a proportion of the additional harvested stem wood is transported to saw mills to produce timber for construction and wooden pallets, thereby displacing marginal saw log production and plastic pallets, respectively. The cost of transportation imposes a constraint on this scenario, as in order to avoid an empty inward journey to the east of Scotland the haulage trucks are assumed to carry biomass to the bioheat plant, in proportion to the quantity of higher quality stem wood transported out. The marginal impact of the demand for inward-hauled biomass is assumed to be increased production overseas, as in scenario 1.1. The alternative local production sub-scenario (2.1) assumes that whole trees are chipped and combusted, and therefore all of the marginal supply may come from increased local production. However, the plausibility of this scenario may be questioned given that other bioenergy plants are expected to put pressure on existing local woody biomass supply (Fife Council, 2013), and the costs of

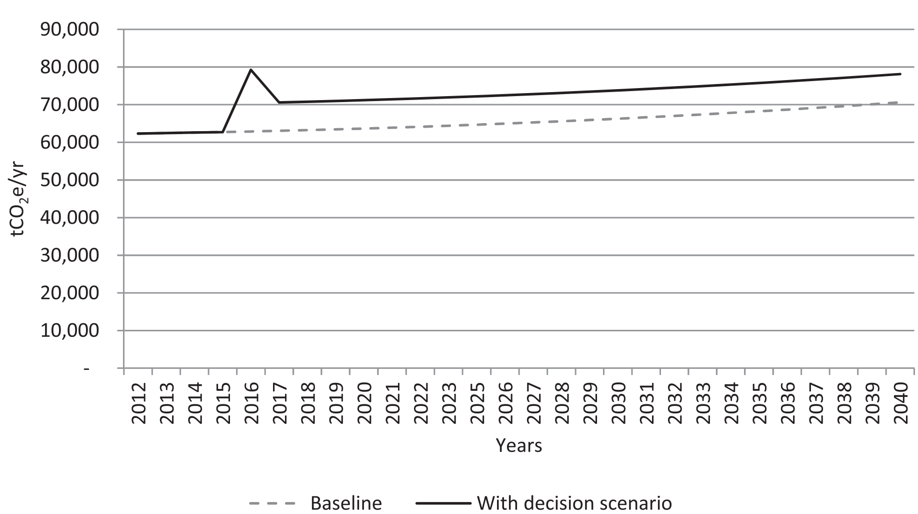

Fig. 3. Corporate GHG inventory – scopes 1, 2, and 3 + biogenic CO_2.

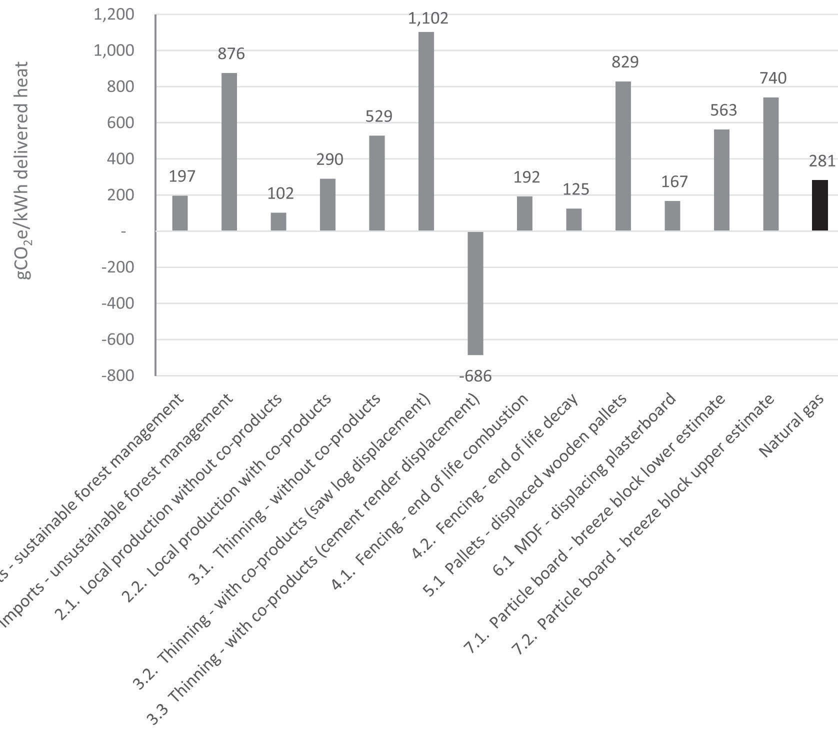

Fig. 4. Results from the consequential LCA.

harvesting small and steep-sloped woodlands may restrict the viability of sourcing biomass that would not otherwise be utilised (Fife Council, 2013; Walker, 2009).

3. Findings

This section presents, in turn, the results from the attributional corporate inventory method; the consequential LCA; the project/policy method; and a comparison of the results from the different methods.

3.1. Corporate greenhouse gas inventory

Fig. 2 presents the results for scopes 1, 2, and 3 of the corporate inventory. There is a very small initial increase in emissions due to the embodied emissions and construction of the bioheat plant (reported under 'capital goods' in scope 3 (WBCSD/WRI, 2011a)), before there is an apparent reduction in emissions due to reduced natural gas combustion.

The accounting rules for corporate inventories state that biogenic CO_2 emissions (i.e. CO_2 emissions from the combustion of biomass) should not be reported within scopes 1, 2, and 3, but should be reported separately. Fig. 3 presents the results for scopes 1, 2, 3, and biogenic emissions. This version of the inventory shows the same initial increase in emissions, but also an underlying increase in total greenhouse gas emissions as the release of biogenic CO_2 is greater than the baseline release of fossil CO_2 from natural gas combustion. This is because natural gas has lower point-of-combustion CO_2 emissions per unit of energy, and the overall efficiency of natural gas boilers tends to be higher than biomass boilers. However, the results in Fig. 3 should be interpreted with caution as although the upstream emissions from the production of the woody biomass are included in the inventory (reported under 'fuel and energy related activities' in scope 3 (WBCSD/WRI, 2011a)), the sequestration of CO_2 that occurs during the growth of the biomass is generally not included in the emission factors used for corporate greenhouse gas accounting (for example, see Defra/DECC (2015)). If this sequestration were included then the results would be identical to those in Fig. 2. The overall finding is that the use of an attributional corporate inventory *would* support the decision to implement the bioheat plant, with an average reduction in emissions of 7083 tCO_2e/yr (assuming the otherwise continued use of natural gas). However, as will be discussed further below, this apparent reduction is only within the sources/sinks included in the inventory boundary, and does not necessarily represent a reduction in total system-wide emissions.

3.2. Consequential life cycle assessment

Fig. 4 presents the results from the consequential LCA in gCO_2e/kWh of delivered heat (i.e. per functional unit). There is a very wide variation in the results, depending on the scenario modelled. All the scenarios with emissions lower than 281 gCO_2e/kWh (the natural gas reference case) entail that the bioheat plant will reduce emissions, and all the scenarios with emissions higher than the reference case indicate the bioheat plant will increase emissions.

The results for scenario 3.3 (increased thinning with the additional availability of sawlogs replacing cement render) show net negative emissions as the emissions avoided by the substitution of cement render are greater than the emissions from the rest of the life cycle.

3.3. Project/policy-level accounting

Fig. 5 presents the results from the project/policy-level method. The results are for the total net change in emissions/removals caused by the decision to implement the bioheat plant. Negative results (below the horizontal axis) indicate that the decision creates a net reduction in emissions, and positive results (above the horizontal axis) indicate that the decision creates a net increase in emissions. The scenarios which create increases or reductions in emissions are the same as those from the consequential LCA, though it is important to note that the presentation of the results is slightly different. The outputs from the project/policy method already show the total change in emissions caused by the decision (baseline emissions/removals minus decision scenario emissions/removals), and no further subtraction of a comparator product's emissions are required.

In addition to the total net change in emissions/removals, the project/policy level method also provides information on the distribution of emissions and removals over time, as both baseline and decision-scenario emissions/removals are calculated as a time-series. Consideration of temporal information is proposed in dynamic LCA (Levasseur et al., 2010; Collinge et al., 2012; Collet et al., 2013; Helin et al., 2013), however conventional (i.e. static) consequential LCA is used in the present study as this is the approach set out in the existing guidance literature (Weidema et al., 2009), and the comparison of the time-series (project/policy method) and non-time-series (standard consequential LCA) approaches also serves to illustrate the importance of further developing and mainstreaming dynamic LCA.

The time-series output from the project/policy method is illustrated in Fig. 6, using the example of scenario 1.1 (the time-series outputs for the other scenarios are provided in the online supporting material). There is an initial increase in emissions due to the embodied emissions of the bioheat plant, followed by a period of high emissions due to the higher point-of-combustion emissions from biomass compared to natural gas. After the assumed 25 year lifetime of the bioheat plant the underlying trend in forest regrowth becomes apparent, and the level of sequestration in the decision scenario is greater than in the baseline. The emissions payback point (i.e. the point at which the cumulative decision scenario emissions/removals equal the cumulative level of emissions/removals in the baseline) is reached in year 75.

Table 3 below shows the results from the project/policy level method (with negative numbers indicating a net lifetime reduction in emissions, and positive numbers indicating a net lifetime increase), and the emissions payback period for the scenarios that incur an initial carbon debt which is compensated for by subsequent reductions in emissions/enhancements in removals. The payback periods range between 1 and 103 years, and are determined by a number of factors such as the regrowth rate of the forest and the embodied emissions of the products displaced by the production of forestry co-products in the decision scenario (which is the reason for the outlier payback period of 1 year for cement render displacement in scenario 3.3).

It is worth noting that the emissions payback periods presented above relate only to the quantity of emissions/removals, and not to the amount of warming caused. For example, if a 100tCO_2 increase in emissions in 2015 is compensated by a 100tCO_2 increase in removals in 2050, the emissions payback point will be 2050, although the amount of atmospheric warming in the decision scenario will still exceed the amount in the baseline. In addition, the payback periods above do not account for the possible atmospheric decay of CO_2. There is an on-going debate within the literature on whether and how to treat different temporal emission/removal profiles (Brandão et al., 2013).

3.4. Comparison of the results from the different methods

Although the methods used tend to present their results using different metrics, Table 4 presents the results from the different methods using the common metric of total lifetime change in emissions in order to allow a direct comparison (with negative numbers indicating a net lifetime reduction in emissions, and positive numbers indicating a net lifetime increase). The corporate inventory provides a single result as this method accounts for the emissions (including supply chain emissions) associated with the direct physical biomass combusted, and therefore does not model alternative scenarios for the marginal systems affected by the increased demand for biomass. It is also worth noting, as above, that the results for the consequential LCA and the project/policy

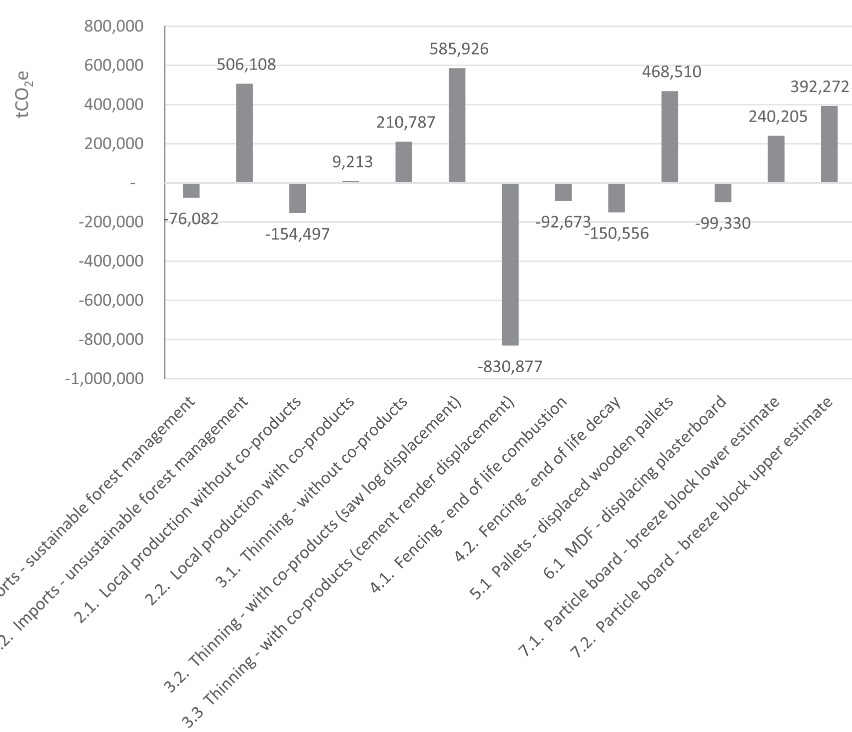

Fig. 5. Results from the project/policy level method.

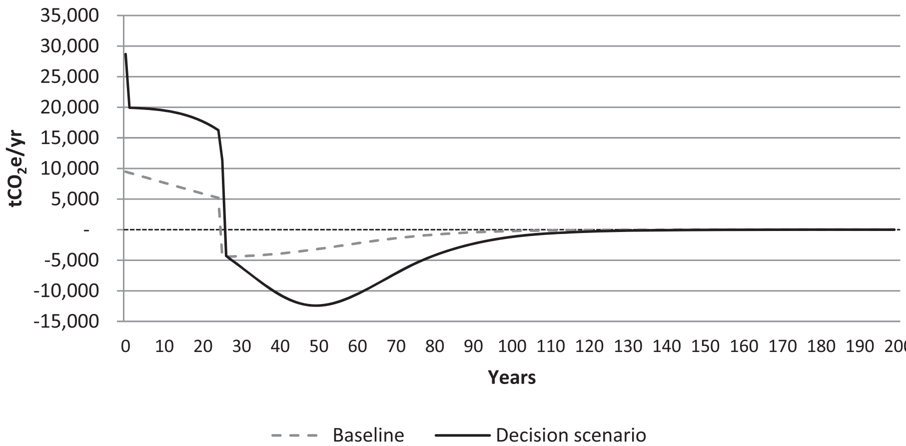

Fig. 6. Project/policy method times-series results for scenario 1.1 (overseas production with sustainable forest management).

method are largely the same, with small differences due to the use of temporally dynamic emission factors for the project/policy method. The corporate inventory indicates that the bioheat plant will reduce emissions, whereas the consequential methods show a range of possible outcomes, including possible increases in net emissions (the interpretation of which is explored in the Discussion (4.3)).

4. Discussion

The following discussion is structured around the following topics: the implications of the findings for attributional corporate greenhouse gas inventories (and attributional methods more generally); the relative merits of project/policy level assessment compared to consequential LCA; and the implications of the findings for the use of bioenergy as a climate change mitigation option.

4.1. Implications for corporate greenhouse gas inventories

As expected, given their attributional nature and the evidence available within the LCA literature, the corporate inventory does not provide information on the total consequences of the decision at hand. Nevertheless, the empirical findings are useful for illustrating the magnitude of difference between the attributional and consequential approaches, in terms of the sources/sinks included. For example, Fig. 7 below presents the causal-chain map for scenario 4.2 (substitution of wooden fencing with concrete fencing, and assuming wooden posts would be combusted at the end-of-life) in order to illustrate the limited scope of the corporate inventory method. The emission sources/sinks indicated with the solid border are those included within the operational boundary of the corporate inventory (including all relevant scope 3 emission sources), and therefore the changes caused in the remaining sources/sinks in Fig. 7 are not accounted for using the corporate inventory method. One exception to this situation is scenario 2.1. (local production with whole tree combustion), in which the sources/sinks included in the corporate inventory coincide with those identified by the consequential methods.

This limitation with corporate greenhouse gas inventories is recognised to some extent in the GHG Protocol *Corporate Standard*, which states that “some companies may be able to make changes to their own operations that result in GHG emissions changes at sources not included in their own inventory boundary” (WBCSD/WRI, 2004, p.61). However, the *Corporate Standard* also states that corporate GHG inventories “provide business with information that can be used to build an effective strategy to manage and reduce GHG emissions” (WBCSD/WRI, 2004, p.3) and that accounting “for emissions can help identify the most effective reduction opportunities.” (WBCSD/WRI, 2004, p.11), without the accompanying caveat that corporate inventories are not sufficient for capturing the total consequences of the reduction options under consideration.

The GHG Protocol *Corporate Value Chain (Scope 3) Standard* offers some additional clarification by stating that ‘in some cases, GHG reduction opportunities lie beyond a company's scope 1, scope 2, and scope 3 inventories' and that accounting ‘for avoided emissions that occur outside of a company's scope 1, scope 2, and scope 3 inventories requires a project accounting methodology’ (WBCSD/WRI, 2011a, p.107). However, as well as the omission of biogenic

Table 3
Net emissions and carbon payback periods from project/policy level method.

Scenario	Sub-scenario	Net emissions from intervention (tCO_2e)	Emissions breakeven point (years)
1. Imports	1.1. Imports - sustainable forest management	−76,082	75
	1.2. Imports - unsustainable forest management	506,108	NA
2. Local production	2.1. Local production without co-products	−154,497	93
	2.2. Local production with co-products	9213	NA
3. Thinnings	3.1. Thinning - without co-products	210,787	NA
	3.2. Thinning - with co-products (saw log displacement)	585,926	NA
	3.3 Thinning - with co-products (cement render displacement)	−830,877	1
4. Fencing	4.1. Fencing - end of life combustion	−92,673	56
	4.2. Fencing - end of life decay	−150,556	58
5. Pallets	5.1 Pallets - displaced wooden pallets	468,510	30
6. MDF	6.1 MDF - displacing plasterboard	−99,330	103
7. Particle board	7.1. Particle board - breeze block lower estimate	240,205	NA
	7.2. Particle board - breeze block upper estimate	392,272	NA

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Table 4
Comparison of lifetime change results from the different methods.

Scenario	Total change in emissions/removals (tCO_2e)		
	Corporate inventory	Consequential LCA	Project/policy method
1.1. Imports - sustainable forest management	−177,070	−72,538	−76,082
1.2. Imports - unsustainable forest management		509,653	506,108
2.1. Local production without co-products		−153,407	−154,497
2.2. Local production with co-products		7745	9213
3.1. Thinning - without co-products		212,158	210,787
3.2. Thinning - with co-products (saw log displacement)		704,276	585,926
3.3 Thinning - with co-products (cement render displacement)		−829,416	−830,877
4.1. Fencing - end of life combustion		−76,414	−92,673
4.2. Fencing - end of life decay		−134,298	−150,556
5.1 Pallets - displaced wooden pallets		469,691	468,510
6.1 MDF - displacing plasterboard		−98,149	−99,330
7.1. Particle board - breeze block lower estimate		241,386	240,205
7.2. Particle board - breeze block upper estimate		393,453	392,272

emissions as part of the corporate inventory boundary (alongside scopes 1, 2 and 3), there is also no explicit recognition that company actions may also cause *increases* in emissions (i.e. leakage), as well as reductions, outside the corporate inventory. Furthermore, there are many instances in the standard which imply that a scope 1, 2, and 3 inventory provides complete information for managing GHG emissions, e.g. "increasingly companies understand the need to also account for GHG emissions along their value chains and product portfolios to comprehensively manage GHG-related risks and opportunities" (WBCSD/WRI, 2011a, p.3), and a "complete GHG inventory therefore includes scope 1, scope 2, and scope 3" (WBCSD/WRI, 2011a, p.27).

The same presumption that a scope 1, 2, and 3 inventory provides complete information for decision-making is present in much of the academic literature on scope 3 (Downie and Stubbs, 2013; Huang et al., 2009; Minx et al., 2009). For instance Downie and Stubbs suggest, in their discussion of scope 3 emissions, that the application 'of HLCA [Hybrid life cycle assessment] methods has the potential to improve the validity of the respondents' GHGE [greenhouse gas emissions] assessments by ensuring they are comprehensive in capturing all relevant and material sources of emissions to the organisation and removing the current subjectivity in emission source selection' (Downie and Stubbs, 2013, p.162). However, the findings from the present study clearly demonstrate that even complete scope 1, 2, 3 (plus biogenic emissions) inventories do not capture all 'relevant and material sources of emissions to the organisation', if the intention is to mitigate climate change.

A broader point illustrated by the findings is that the attributional-consequential distinction can be used as a generic categorical scheme for drawing inferences about methods of the same categorical type. That is, by recognising that corporate inventories are attributional in nature we can draw useful inferences based on what we know about other forms of attributional inventory, such as attributional LCA. Reciprocally, the empirical illustration of the omission of sources/sinks that change within attributional corporate inventories can also be used to infer support for, and provide further impetus to, the already growing

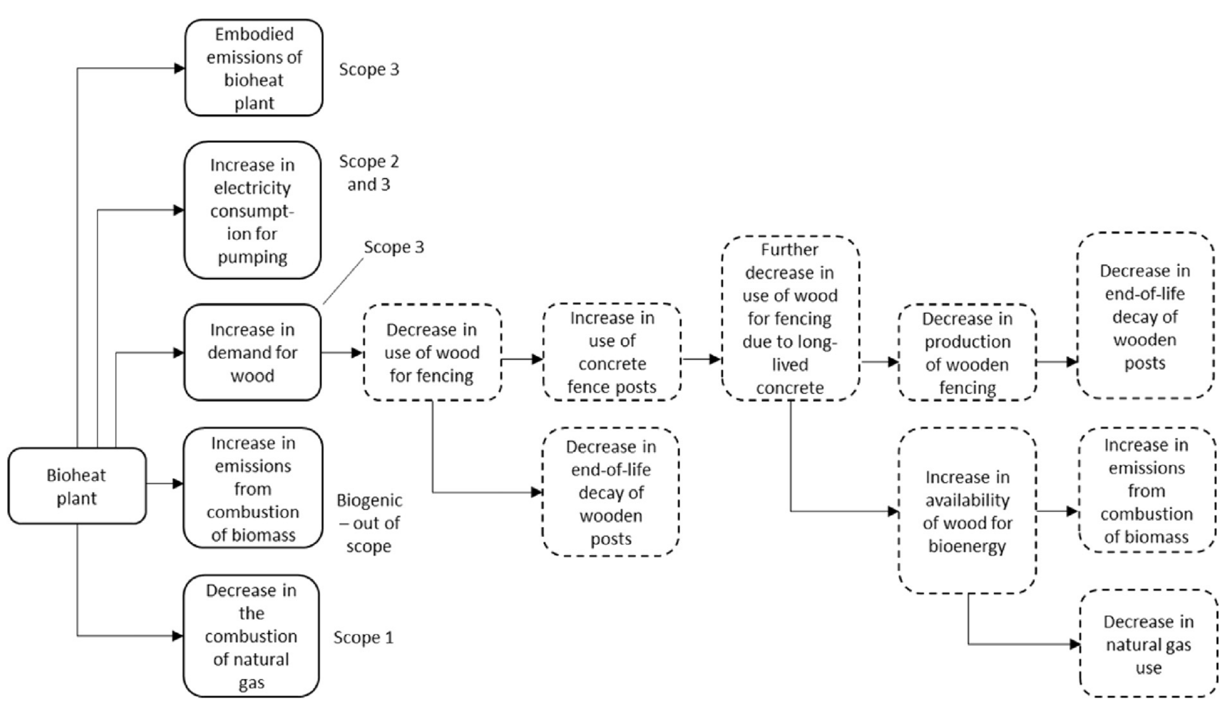

Fig. 7. Causal-chain map for scenario 4.2.

recognition of the limitations with attributional LCA, noted earlier. The same inference can also be made to other forms of attributional method, such as national inventories and community inventories, i.e. due to their attributional nature these methods will not necessarily capture total change in emissions, and therefore are not sufficient for informing mitigation decisions.

Although the above discussion highlights the insufficiency of attributional methods for mitigation decision-making, it is highly important to emphasize that attributional methods do have other appropriate uses, for which consequential methods are not suitable. For example, attributional inventories are useful for assigning initial responsibility for managing a set of environmental impacts; for setting reduction targets; and for setting carbon budgets to ensure total emissions do not exceed an aggregate threshold (Brander, 2015a, 2016). Though, again, any actions undertaken to mitigate emissions or achieve reduction targets should be informed by a consequential method to ensure that the action does not have unintended consequences. The following section now discusses the relative merits of the different forms of consequential method.

4.2. *Difference between consequential LCA and project/policy accounting*

In contrast to the corporate inventory method, both consequential LCA and project/policy level assessment aim to quantify the total system-wide change in emissions caused by the decision at hand. Although both approaches reach broadly the same results (in terms of the magnitude of increase or decrease in emissions/removals for each scenario), they derive and present the results in different ways, and provide different amounts of information on the temporal distribution of emissions/removals. The following discussion focuses on the differences between the project/policy method and consequential LCA, as characterised in the guidance documents used for the present study (Ekvall and Weidema, 2004; Weidema et al., 2009; European Commission et al., 2010), noting that other characterisations of consequential LCA exist (e.g. Plevin et al. (2014b)).

One initially superficial difference, but which may obscure more significant issues, is the presentation of the results at either the unit or aggregate level, i.e. the consequential LCA results are in gCO_2e/kWh while the project/policy method shows total aggregate change in tCO_2e. This can be viewed as a superficial difference as either metric can be converted into the other, e.g. by subtracting the natural gas comparator figure from the unit level consequential LCA result and multiplying by the total delivered heat output of the plant (or the reverse for converting from the aggregate figure to the unit level). However, one potential shortcoming with focusing the analysis at the unit level is that non-linearities of scale are more likely to be missed, and despite the guidance to the contrary (Weidema et al., 2009), many consequential LCA studies do not state what the aggregate-level decision is assumed to be (Brander, 2015b). Furthermore, presenting the results at the unit level may also create the misleading impression that the decision itself can be disaggregated, whereas, in the case of the bioheat plant, the decision only relates to the plant as a whole, and not to individual incremental units of heat consumption.

Losing sight of the aggregate-level decision can also lead to the use of arbitrary amortisation periods, and therefore arbitrary aggregate output levels for calculating unit-level results. If the unit-level results are to represent the change in emissions (*caused by the decision*) per unit of output (*caused by the decision*), then the denominator must be based on the specific decision at hand, and not the amount of production occurring during an arbitrary or conventional amortisation period. In the case of the bioheat plant, the total expected output during a 25-year period is used, as this is the expected lifetime of the plant in question, and the production of heat during this period is amount of output caused by the decision.

Another seemingly superficial difference between the methods, but one which may also have more significant implications, is the differing structures in terms of baseline net emissions (emissions minus removals) and decision-scenario net emissions. Consequential LCA results represent a combination of both decision scenario net emissions and credits for the avoidance of some baseline scenario net emissions. For example, the result of 125 gCO_2e/kWh for scenario 4.2 (displacement of wooden fencing) includes a credit for the displaced emissions from the end-of-life decay of the fencing. Such results can then be compared to the consequential LCA results for other products, or if the product studied is replacing an alternative, then the total change in emissions is estimated by subtracting the results for the reference case from the results for the proposed substitute product.

This comparison of consequential LCA results to a reference case is not straightforwardly equivalent to the comparison between baseline and decision scenario net emissions in the project/policy method, as discrete consequential LCA results represent a *mixture* of baseline and decision scenario net emissions, as noted above. One possible benefit of the project/policy method is that it is conceptually easier to understand. For example, the displacement of the end-of-life emissions from the wooden fencing is treated as a negative input to the product-system studied in consequential LCA (Weidema et al., 2009), but it is difficult to conceive of what a negative input is (Brander, 2015b). In contrast, for the project/policy method, the displaced end-of-life emissions are simply included in the baseline, but do not occur in the decision scenario. Similarly, other effects that are awkward to accommodate in consequential LCA, such as foregone sequestration, rebound effects, and non 1:1 substitution ratios, can be straightforwardly modelled as differences between the baseline and decision scenario.

Turning to the issue of the distribution of emissions over time, consequential LCA, as defined by the methodological guidance documents used in this study, does not provide information on the temporal distribution of impacts, and moreover, is generally only concerned with quantifying normalised emissions for the long-run marginal system, based on the assumption that the long-run system will dominate the overall change caused by the decision in question (Weidema et al., 2009; Schmidt et al., 2015). In distinct contrast, the project/policy method provides a time-series of emissions/removals (illustrated in Fig. 6), and this appears to constitute a major advantage over conventional static consequential LCA.

Firstly, information on the temporal distribution of emissions allows the calculation of the carbon payback period (for those scenarios that do eventually payback), which is highly decision-relevant given concerns about climate tipping points (Lenton et al., 2008) and the near and medium–term nature of most reduction targets (UK Government, 2008; European Commission, 2015). Secondly, the time-series approach allows temporally-specific emission factors to be applied to activity data. For example, in the present study the emission factors for road, rail and sea freight used in the project/policy method decline over time to reflect the expected increase in transportation fuel efficiency (and although this only makes a slight difference in the overall results, for other studies the difference could be considerable). Thirdly, the time-series approach allows the transition between different marginal systems to be modelled, e.g. the short, medium and long-term systems. For example, it is possible that the marginal system in the short-run will be increased production overseas (scenario 1) before transitioning to increased local production (scenario 2) as local capacity develops (Alexander et al., 2013). Although this transition modelling is not undertaken in the present study, the structure of the project/policy method has the inherent flexibility to allow such modelling, whereas consequential LCA does not. There is growing recognition within the LCA community for the need to include a temporal dimension to the method (Levasseur et al., 2010; Brandão et al., 2013; Collet et al., 2013; Schmidt et al., 2015), and a possible fast-track to achieving this would be to adopt the time-series structure from the project/policy approach.

Reverting briefly to the corporate inventory method, it is interesting to note that despite its other shortcomings this method does provide a partial time-series of emissions. However, corporate inventories tend to track the activities that occur in the inventory year, rather than the emissions/removals that occur in that time-period (WBCSD/WRI, 2011a, p.32). For example, the total life-time emissions from landfilled waste are generally reported in the year that the waste is produced, rather than showing the distribution of emissions from the waste at the time that the emissions occur. Similarly, for some scope 3 emission sources, such as 'purchased goods and services' and 'fuel and energy related activities', attributional LCA emission factors are used to calculate emissions, and the non-temporally-explicit nature of attributional LCA is therefore imported into the corporate inventory. In the case of the 'fuel and energy related activities' for woody biomass, the attributional LCA emission factors published for corporate reporting (e.g. Defra/DECC (2015)) do not show the potentially long regrowth/sequestration period following the harvesting of the biomass.

4.3. Implications for bioenergy policy

The results from the consequential methods suggest that the case for the bioheat plant is not clear, and it is highly plausible that the decision to implement the plant will increase global CO_2e emissions rather than reduce them. Although considerable care is required in interpreting the results it is still possible to derive decision-relevant conclusions about the case for bioenergy.

However, before discussing the implications of the results, the following important caveats should be noted. Firstly, a large number of assumptions and modelling choices were made when implementing the consequential methods, and the selection of alternative parameter values will alter the results. Nevertheless, the findings from the sensitivity analysis (provided in the online supporting material) indicate that although the results for individual scenarios vary with alternative parameter values, the overall finding of large differences in the possible outcomes from the bioheat plant remains. Secondly, the range of scenarios tested is not exhaustive, and there are many other plausible scenarios that could be modelled (e.g. a scenario in which wind-blown trees are utilised, or in which increased demand for biomass increases tree planting (as suggested by Daigneault et al. (2012), Favero and Mendelsohn (2013), and Latta et al. (2013))). Thirdly, the results are presented for each individual scenario, whereas in reality there is likely to be a mix of marginal systems affected by the decision (Ekvall and Andræ, 2006; Schmidt, 2008; Mathiesen et al., 2009), and also a transition between combinations of scenarios over time (ideally a general equilibrium model would be used to capture the complexity of market responses, and the changing combination of marginal systems over time). Fourthly, the relative likelihood of each scenario is not estimated, and it is not possible to infer that one scenario or outcome is more likely that another (although an initial review of the evidence suggests a strong case for increased overseas production). The development of further scenarios, and the estimation of expected likelihood should be the subject of further research. Finally, 1:1 substitution ratios are assumed in the calculations, e.g. 1 kWh of delivered heat from the bioheat plant will substitute 1 kWh of delivered heat from a natural gas boiler. This assumption was used in the absence of readily available values for the elasticities of demand and supply, however, it is highly important to note that substitution ratios can differ significantly from the 1:1 ratios assumed in this study (Chalmers et al., 2015).

Notwithstanding the numerous caveats with the consequential results it is still possible to draw substantive conclusions from the findings, especially when the range of possible outcomes is *itself* recognised as a key finding (Plevin et al., 2014b). The situation with the bioenergy plant can be characterised as one of Knightian uncertainty (Knight, 1933), as the probabilities of the different possible outcomes are not known. One decision-making strategy offered by normative decision theory for dealing with situations of Knightian uncertainty is to adopt the 'maximin' principle (Zaharatos, 2014), whereby the maximum possible loss from the decision is minimised. With this in mind, it would be useful to undertake similar consequential studies for alternative mitigation technologies, such as wind energy or ground-source heat, and to identify whether there are plausible scenarios in which these options increase emissions. If there are not, this would justify prioritising those options over bioenergy.

A further possible interpretation involves appeal to the normative principle that good decisions are those that achieve or maximise the desired outcomes of the decision-maker (Rapoport, 1989). Given that the desired outcome of the decision-maker is to mitigate climate change, and the uncertainty as to whether the bioheat plant will achieve or hinder this outcome, it is not possible to justify implementing the bioheat. Or to put it another way, the information available equally supports *not* implementing the bioheat plant. This interpretation is distinct from the maximin strategy, above, as no comparison with alternative mitigation options is required to reach the conclusion that the bioheat plant is not justified. One possibility for addressing this lack of justification for the bioheat plant is to explore the likelihood of the possible emissions outcomes e.g. studies on the expected supply of biomass such as Lauri et al. (2014) can be used to inform a subjective assessment of the likelihood of increased overseas production.

In addition to the above, the potentially long emission payback periods for the bioheat plant tallies with the findings of numerous other studies (Walker et al., 2010; Mitchell et al., 2012; Bernier and Paré, 2013; Holtsmark, 2012, 2013; Jonker et al., 2014; McKechnie et al., 2011; Pingoud et al., 2012; Schulze et al., 2012; Zanchi et al., 2012), and is highly relevant information to the decision at hand. The long emission payback periods entail that the bioheat plant may cause emissions to increase up to and beyond 2050, which is commonly used as the target year for reduction commitments (UK Government, 2008; UK Government, 2012; European Commission, 2015), and may contribute to a climate tipping point before net emissions are reduced (Lenton et al., 2008).

A number of studies suggest that bioenergy does not create a carbon debt if a 'landscape' level of analysis is used, as the carbon stock of the whole forest estate will be relatively constant over time if it is sustainably managed, although the carbon stock of individual stands will change during the growth and harvesting cycle (Mitchell et al., 2012; Zanchi et al., 2012; Adams et al., 2013; Smith and Bustamante, 2014). However, constant landscape-level carbon stocks are misleading as the relevant issue is whether those carbon stocks would have been higher (or lower) in the absence of the decision in question. Studies which take a properly consequential landscape-level approach still find a large carbon debt (e.g. Haberl et al. (2013)), which in some scenarios is never paid back (Hudiburg et al., 2011; Holtsmark, 2013).

Although the present study focuses on the change in emissions/removals caused by the implementation of an individual bioheat plant, the key finding on the range of possible outcomes is expected to apply to any bioenergy installation using woody biomass, given the interconnected and global nature of the market

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for wood. One implication of this is that additional consequential assessments are not necessarily needed for each bioenergy installation within the market, as the marginal impact (or range of possible impacts) will be largely the same. This partly addresses the criticism that consequential analyses are too costly to implement (Rajagopal and Zilberman, (2013)), as a single assessment may be broadly applicable to all decisions impacting the same market (Weidema, 2003).

Similar findings to those from the present study are expected to apply at the level of government policy for bioenergy, where the system-wide impacts from bioenergy policies are also likely to be highly uncertain, and with long payback periods. As a further point, policy measures involving attributional supply chain reporting, such as that under the Renewable Energy Directive (European Parliament and Council of the European Union (2009)), are likely to be irrelevant for ensuring that bioenergy policies do not increase emissions, given that attributional methods do not capture the total system-wide impacts of the intervention studied.

5. Conclusions

A number of conclusions can be drawn regarding greenhouse gas accounting methods. Firstly, as expected given their attributional nature, conventional corporate inventories are not sufficient for supporting mitigation decision-making, even with full scope 3 reporting. It is recommended that existing greenhouse gas accounting standards clarify that corporate inventories should only be used for purposes such as assigning responsibility for a set of emission sources, emission reduction target setting, or carbon budgeting (Brander, 2015a), and that consequential methods must be used to inform mitigation decisions. The same limitations, and therefore the same recommendations, apply to the use of all forms of attributional accounting, including national greenhouse gas inventories, community-level inventories, and attributional product LCA.

Secondly, of the consequential methods studied, the project/policy method appears to have a number of advantages over consequential LCA, namely the transparent and conceptually simpler baseline and decision scenario structure, and the ability to show the distribution of impacts over time. There is already recognition within the LCA community of the need for dynamic (i.e. temporally explicit) modelling, and one option is to adopt the structure used in the project/policy approach. However, it is also worth noting that the consequential LCA literature includes numerous heuristics and techniques for identifying marginal systems, and the sharing of methodological lessons should very much be a two-way process.

Thirdly, a broader conclusion can be drawn on the utility of the attributional-consequential distinction as a generic categorical framework for understanding the nature of different forms of physical greenhouse gas accounting. The present study provides an empirical illustration of the possibilities opened up by this framework, i.e. the possibility of inferring the appropriate use of a method, and the possibility of transposing lessons between methods, based on their categorical type.

A final conclusion concerns bioenergy as a climate change mitigation option. The uncertainty of the emissions outcomes should *itself* be viewed as a decision-relevant finding from the present study, and further research should investigate the range of possible outcomes from alternative mitigation options, with preference then given to those without the potential for large undesirable outcomes. Furthermore, even in the scenarios where the bioheat plant achieves a net lifetime reduction in emissions, the payback period may extend beyond 100 years, thereby contributing to nearer-term cumulative emissions and a possible climate tipping-point, as well as making the intervention irrelevant to near and medium-term reduction targets.

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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.jclepro.2017.02.097.

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