Carbon payback times of wood pellets from different feedstock types produced in the south-eastern United States and used for bioelectricity in the Netherlands

Master Thesis
MSc Energy Science
July 2015
Steef Hanssen

Supervisors:
dr. Floor van der Hilst
Anna Duden MSc

Universiteit Utrecht

Cover photo: Pine-and-Oak forest in the Great Smoky Mountains National Park, on the border of Tennessee and North-Carolina. April 7th 2015, © S. V. Hanssen

Disclaimer

The knowledge and experience shared by various forest and wood pellet stakeholders and experts formed an important input to this study (see annex III). This input was highly valued (please refer to the acknowledgements section for specifics). The author would like to stress that the views expressed in this thesis are those of the author (coming forth from his analysis), and do not necessarily reflect the position of any expert or stakeholder that provided input for this thesis.

Abstract

The Netherlands imports wood pellets (a type of solid biofuel) from the south-eastern US to co-fire them in power plants, with the aim of mitigating climate change and achieving European renewable energy targets. The use of wood pellets to generate electricity results in extraction of carbon from the environment and greenhouse gas emissions to the atmosphere. Carbon payback times reflect the time interval during which using wood pellets causes larger net emissions than the (fossil) reference system; hence carbon payback times are highly relevant to judge whether using wood pellets mitigates climate change within policy relevant timescales. This study compared carbon payback times of bioelectricity that is generated using wood pellets from four different feedstock types (low-quality roundwood, thinnings, harvest residues and mill residues). Furthermore, two differen tree types (softwood and hardwood), and two temporal perspectives on the referene amount of carbon in the system were studied (just before harvesting vs. when trees start growth). Both carbon debt payback times (comparing wood pellet bioelectricity to the fossil refrence system only) and carbon parity payback times (comparing wood pellet bioelectricity to a counterfactual scenario) were determined. The choice of wood pellet feedstock does not substantially affect carbon debt payback times of wood pellet bioelectricity, except when thinnings are used as feedstock– resulting in shorter carbon debt payback times. When reference carbon stocks are determined at the moment trees start growth (rather than just before harvesting), carbon debt payback times of wood pellet bioelectricity are zero years. Carbon parity payback times vary substantially. Wood pellet feedstock itself hardly affects carbon parity payback times, but does determine what counterfactual scenarios are applicable. The counterfactual does strongly influence carbon parity payback times: when feedstock is left to decompose or used in traditional forest products carbon parity payback times are relatively short, when feedstock is not harvested at all carbon parity payback times are relatively long. Using feedstock material to provide heat locally results in carbon parity never being reached, whereas burning feedstock materials without energy capture results in instant carbon parity. The selection of counterfactuals used in this study is larger than previous studies and may better reflect reality. Results on feedstock and counterfactuals showed considerable uncertainty, but thinnings seem the best wood pellet feedstock in terms reducing the carbon impact of wood pellet based bioelectricity. In most cases carbon payback times of wood pellet bioelectricity are shorter when softwood pellet feedstocks are used. In almost all cases the temporal perspective on reference system carbon stocks does not affect carbon parity payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US. This result suggests that temporal perspective should not substantially influence the outcome of the wood pellet bioelectricty's carbon balance and resulting policy decisions, as long as counterfactuals are properly accounted for. To improve the climate mitigation effect of using wood pellets from the US South-East to provide Dutch power, the next should be to get an even better understanding of what exact (mix of) counterfactuals is relevant for a feedstock. Using this information, feedstock selection could be optimised for climate benefits – within the boundaries posed by costs of feedstock and technical possibility to process different feedstocks at the various pellet mills in the US South-East.

Contents

1. Introduction

In 2009 the European parliament and council adopted the European Directive on Renewable Energy Sources (2009/28/EC) to combat climate change and reduce Europe's energy imports from unstable regions and associated geopolitical vulnerability. The directive obliges European member states via individual targets to on average reduce greenhouse gas (GHG) emissions by 20%, increase energy efficiency by 20% (both as compared 1990 levels) and increase the share of renewable energy sources to 20% of gross final consumption, by the year 2020 (2009/28/EC). The EU is well on track in meeting these three targets; looking specifically at the third target: the share of all renewables in gross final energy consumption was 15% in 2013, up from 10.5% in 2008 (Eurostat, 2015). The largest contributors to this increase were solid biofuels (Eurostat, 2015). By 2020 biomass used for electricity generation and heating *alone* is expected to supply around 8.4% of the EU-wide final energy consumption (based on Lamers et al., 2014a). The country target for the Netherlands is a renewable energy share of 14% of gross final energy consumption in 2020 (2009/28/EC). In 2013, a share of only 4.5% was realised (CBS, 2014), an increase in renewable energy production is thus urgently needed in the Netherlands. As bioenergy makes up 70% of current renewable energy consumption in the Netherlands (CBS, 2014), future increases in the share of renewables can also be expected to be partly or mostly formed by bioenergy.

This study focuses on wood pellets as a source of bioenergy. Wood pellets are a type of solid biofuel made by drying, "hammering" (breaking into small pieces) and compressing woody biomass (e.g. sawdust, chipped forest harvest residues or chipped roundwood) into roughly 3 by 0.5 cm sized pellets. The use of wood pellets can contribute to meeting renewable energy targets by (co-)firing them in power plants to produce electricity, or through their use as residential or district heating fuel (Sikkema et al., 2011; Goh et al., 2013). Wood pellets provided about 0.2% of gross final energy consumption in the EU in 2008 (based on Sikkema et al., 2011). It has increased since and will likely continue to increase, given increases in pellet trade and use. Global wood pellet production was 14-15 Mtonnes in 2010 (Lamers et al., 2012; Goh et al., 2013), almost ten times more than in 2000 (Lamers et al., 2012) and production will continue to grow over the next decade (Sikkema et al., 2011; Lamers et al., 2014a). The EU is the largest global producer and consumer of wood pellets, accounting for 61% of global production and 85% of global consumption of wood pellets in 2010 (Goh et al., 2013).

While the EU as a whole is a net-importer, countries within the EU have different roles with respect to pellet trade (e.g. net importers or exporters within or outside the EU) and pellet use (electricity generation, residential heating or district heating; for an extensive overview see Lamers et al., 2012). The United Kingdom, the Netherlands and Belgium are the main importers of industrial grade wood pellets from outside the EU, which are used to generate electricity through co-firing the wood pellets in power plants, partially replacing fossil fuels (Sikkema et al., 2011; Lamers et al., 2012; Goh et al., 2013). The wood pellet demand of these countries, including the Netherlands, is almost entirely supplied by North America; Canada and the United States delivered 0.926 and 0.736 Mtonnes respectively in 2009 (Lamers et al., 2012). By 2020 the US will become the largest exporter to the EU[1], providing an estimated 5 Mtonnes of wood pellets – or a third of expected 2020 extra EU imports (Lamers et al., 2014a).

The south-eastern US is the dominant wood pellet supply area within the US (Pinchot institute, 2013; Abt et al., 2014); it is estimated that 5.6 Mtonnes of wood pellets will be exported from the region by 2020, which could well be an underestimation considering recent rapid deployment of capacity (Pinchot Institute, 2013) and a *doubling* in wood pellet production since 2011 (Prestemon et al., 2015). European policy-driven demand is the key driver of the US South-East's booming wood pellet market (Sikkema et al., 2011; Abt et al., 2014). Details on the US South-East's forests and their future are given in box 1.

---

[1] The scale of new US pellet plants, their relative proximity to the European market and US subsidies on pellet production are key advantages of the US pellet industry over its Canadian counterpart (Lamers et al., 2012).

Box 1. Forests and woody biomass production in the US South-East

The US South-East comprises 13 states: Virginia, North Carolina, South Carolina, Georgia, Florida, Kentucky, Tennessee, Alabama, Mississippi, Arkansas, Louisiana, and the eastern parts of Oklahoma and Texas (as defined in Wear & Greis, 2012, see figure 1; narrower definitions exist as well, but this does not affect data used in the current study). In this US South-East forests generally exceed 40% of total land cover resulting in 205 million acres (or about 830,000 square km) of forest – both natural and planted (Wear & Greis, 2012). More than half of these forests are categorised as hardwood forests and 19% as pine plantations (see figure 1; Wear & Greis, 2012); these two forest types form the predominant source of wood pellet feedstock. The US South-East is among the most suitable regions for woody biomass production in the world (see figure 2, from: Chum et al., 2011). Since the 1950s pine plantations have expanded tremendously and productivity has increased due to intensive management (Fox et al., 2007). The South currently produces more than 60% of US timber, while the US is the largest global timber producer (Pinchot Institute, 2013).

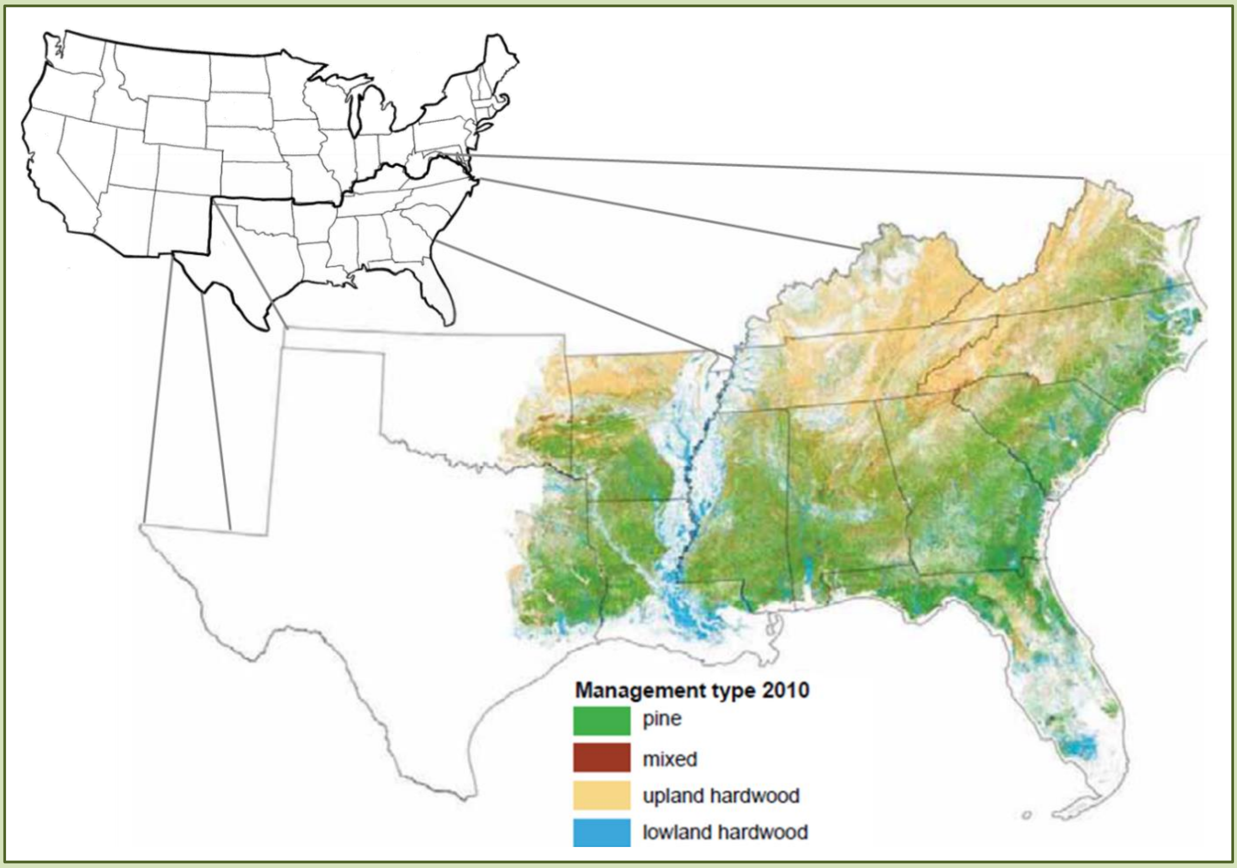


Figure 1. *(Based on Wear & Greis, 2012) Forests in the South-Eastern US. More than half of the 200 million acres of forested area is categorised as hard woods forest, pine plantations cover 19%.*

It is characteristic for the US South-East that as much as 86% of the forests are privately owned: 66% is owned by individuals and families (usually small-landowners) and 20% by corporate foresters (large landowners). The remaining 14% of forestland is owned by states or the federal government (Wear & Greis, 2013). Around 80% of private forests have been commercially harvested at some point (Wear & Greis, 2013). In 2009 private forests produced 96% of the region's roundwood (Johnson et al., 2011). Harvesting, forest management and land use change decisions strongly depend on ownership type (N. Poudyal, personal communication, April 15, 2015); corporate foresters usually aim to maximise land productivity and economic value, small private owners may hold on to forested land (use) for recreational purposes, as an investment or as family heritage – more so than to maximise profits, government forests include state and national parks.

box 1 continued

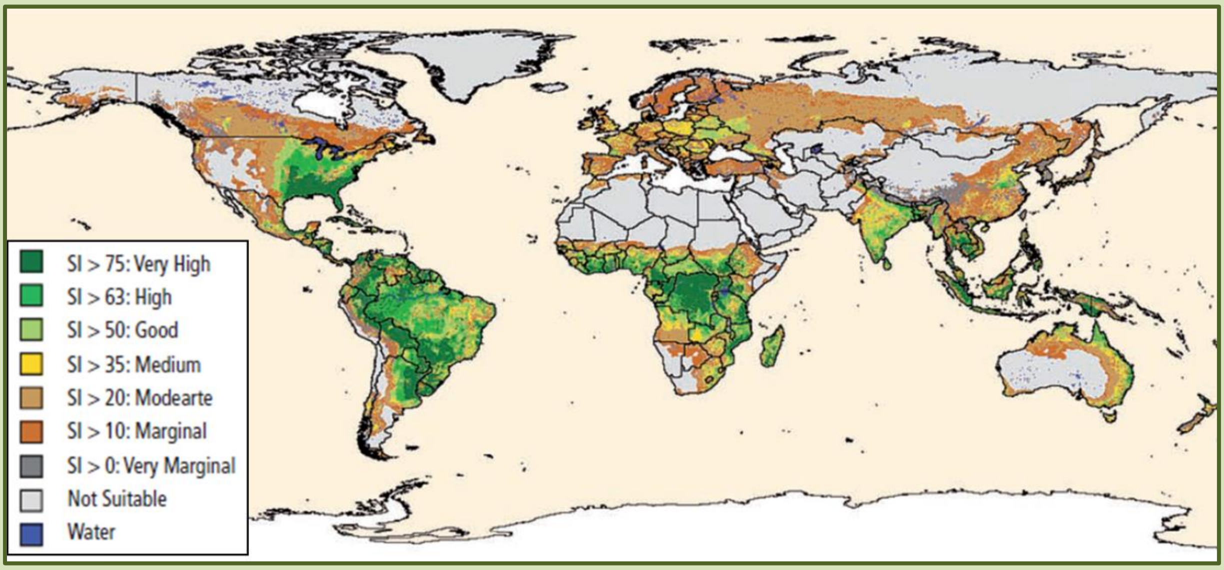


Figure 2. *(From: Chum et al., 2011) Land suitability for bioenergy plantations of herbaceous and woody lingo-cellulosic plants. The US South-East is in the highest suitability category along with other highly productive, often tropical, regions.*

Towards 2060 the US South-East is forecasted to lose 7-13% of forested land, mostly to urban expansion (as compared to 1997 levels; Wear & Greis, 2013). In this period pine plantations may increase by 7-27 million acres as compared to the current 40 million and increase to 24-36% of total forest cover (Wear & Greis, 2013). Carbon storage in forests is expected to peak between 2020 and 2040 and then decline (US Forest Service RPA, 2010; Wear & Greis, 2013).

Woody biomass harvests for bioenergy (including wood pellets) are expected to increase by 54% to 113% over the next forty years (Wear & Greis, 2013). Increased demand for bioenergy will affect traditional wood users, land use and management intensity (Abt et al., 2012). Recently harvests and wood pellet feedstock prices have increased, and in simulations they continue to rise until at least 2020 (Abt et al., 2014). Prices of pellet feedstock depend on (EU) pellet demand, the inelastic demand of traditional uses (timber and paper), the exact feedstock type (sawdust and harvesting residues are cheaper than roundwood) and the inherent inelastic supply response time of tree plantations (trees take decades to grow), all of which have led to the current price increase (Abt et al., 2014). However, the decreased local demand for timber and paper and pulp products (Wear & Greis, 2013), may allow bioenergy to develop without requiring additional land, as suggested by Jonker et al. (2013), and keep feedstock prices in bound.

One of the main goals of the European Renewable Energy Directive (2009/28/EC) is to create a more sustainable energy supply. And although sustainability is considered of key importance by all stakeholders – both American and European (Pinchot Institute, 2013), there are several concerns about the sustainability of producing wood pellets in the US South-East and consuming them for bioenergy production in Europe. Firstly, for wood pellets to be sustainable, they must be truly renewable. This means that biomass growth should exceed removals, which is currently still the case in the US South-East, but stored biomass has started to level off (Wear & Greis, 2012). Secondly, there are risks of biodiversity loss and soil degradation with increased plantation area and biomass outtake (for an overview see Lamers et al., 2013b).

The final and most fundamental sustainability concern is the climate change impact of using wood pellets to produce bioelectricity. If replacing fossil fuels by wood pellets does not reduce overall greenhouse gas (GHG) emissions of electricity (or does not reduce emissions within relevant timescales – the importance of timing is discussed below), wood pellets may still be renewable sensu stricto, but their use would actually increase climate change impacts compared to fossil fuels (or at least increase impacts over a long period of time before net GHG emission reductions are achieved). This would of course be contrary to the desired outcome of European policy[2]. The emissions and sequestration of carbon dioxide (and other greenhouse gases[3]) that are caused by the use of wood pellets for electricity production are described (over time) by its carbon balance. Both the construction and outcomes of the carbon balance of bioenergy in general, and American wood pellets used for Dutch bioelectricity in particular, are under considerable debate in the scientific community (see KNAW, 2015) and recently received more attention in American and Dutch media as well (e.g. NY Times, 2015; Biobasedeconomy.nl, 2015 – in Dutch only).

The *carbon balance* of woody bioenergy is the balance between reduced carbon stocks of a forest due to harvesting or land-use change (LUC, e.g. conversion of an old-growth forest to a tree plantation) on one hand, and carbon sequestration through forest (re)growth and carbon offsets of avoiding emissions from fossil fuels on the other. The initial forest carbon stock reduction due to LUC or harvesting is called the *carbon debt* (Zanchi et al., 2010; Fargione et al., 2008; Lamers et al., 2013a)[4]; the present study distinguishes a harvest-associated carbon debt (carbon extraction through harvesting) and an LUC-associated carbon debt (carbon losses through land use change). The carbon debt is eventually repaid (figure 3), as the forest (re)grows and sequesters carbon after harvesting or LUC, and as harvested forest biomass is used to replace fossil fuels (hence avoiding emissions from fossil fuels[5]). The time interval until repayment is called the *carbon debt payback time* (Schlamadinger & Marland, 1996b; Gibbs et al., 2008; Lamers et al., 2013a)[6].

If the land had not been used for (woody) bioenergy production, it might have sequestered more carbon (Schlamadinger & Marland, 1996b; Marland & Schlamadinger, 1997; Mitchell et al., 2012; Holtsmark, 2012a; Lamers et al., 2014b)[7]. Likewise, if the produced biomass was used differently (e.g. for traditional forest products like paper rather than for bioenergy), a different carbon emission/storage pattern could arise. These 'would-be situations' are called *counterfactual scenarios* (Stephenson & MacKay, 2014). The point in time when the carbon balance of woody bioenergy is equal to that of the counterfactual scenario (i.e. both have the same system-wide carbon effect) is called the *carbon parity* point (Mitchell et al., 2012; see figure 3). The time interval between initial land use change or harvest and the carbon parity point is referred to here as the *carbon parity payback time*.

---

[2] Despite this potential undesired outcome there are currently no EU wide sustainability criteria for imported wood pellets (Kittler et al., 2012). Whether biomass is sustainable or not, and the impact of potential future criteria is considered one of the greatest business uncertainties by European utility companies that import pellets (Kittler et al., 2012). Future trade to the EU is strongly dependent on sustainability criteria (Lamers et al., 2014a), and so is the potential available supply (Abt et al., 2014). Currently, 17% of the US South-East's forests are certified to some sustainable forest management standard (Kittler et al., 2012; Pinchot Institute, 2013).

[3] Carbon dioxide is the most important greenhouse gas associated with the overall production and use of wood pellets to generate electricity (while replacing fossil fuels); hence the *carbon* balance and *carbon* payback times terminology. However, this study did include the (smaller) effect of other greenhouse gases as well, notably methane and nitrous oxide (see chapter 3).

[4] Zanchi et al. (2010) introduced the carbon debt terminiology for forest bioenergy, focusing mostly on the harvest-related carbon debt (adopted by for instance Jonker et al., 2013, McKechnie et al. 2011). Fargione et al. (2008) originally introduced the carbon debt term for (agricultural) bioenergy crops (see also Searchinger et al., 2008), in reference to the LUC-related carbon debt (which can also be relevant for forest bioenergy). For a recent review on the carbon debt of woody bioenergy see Lamers et al. (2013a). The importance of LUC-associated emissions for the bioenergy carbon balance was already acknowledged in the 1990s (e.g. Schlamadinger & Marland, 1996a,b).

[5] Emissions from burning fossil fuels are avoided, i.e. they no longer occur and form net savings compared to fossil system. Emissions from burning biomass were already accounted for in the carbon debt (see section 3.4).

[6] Schlamadinger & Marland (1996b) already described this principle, but the term carbon debt payback time was (to the Author's knowledge) first used by Gibbs et al. (2008) for crop-based bioenergy, since it has has also become widely used in woody bioenergy studies, see Lamers et al., 2013a for an overview.

[7] This also holds for old-growth forests, which continue to sequester carbon (Luyssaert et al., 2008).

Whether wood pellets reduce overall emissions thus depends on the time interval considered (Mitchell et al., 2012). Over time the carbon balance of a wood pellet production system shifts from a net increase in carbon emissions compared to using fossil fuels, to the point where the bioenergy system has the same carbon emissions as the fossil system (i.e. the carbon debt payback point or carbon parity point[8], see figure 3), to net emission reductions compared to fossil fuel use and hence actual carbon benefits (Walker et al., 2010; Mitchell et al., 2012; Zanchi et al., 2012). To assess whether the use of wood pellets for bioelectricity is sustainable from a climate perspective and makes sense within policy relevant timescales, it is crucial to determine the carbon payback times of bioelectricity from wood pellets (Lamers et al., 2013a). Moreover, to shape future policy it is important to determine what variables influence carbon payback times.

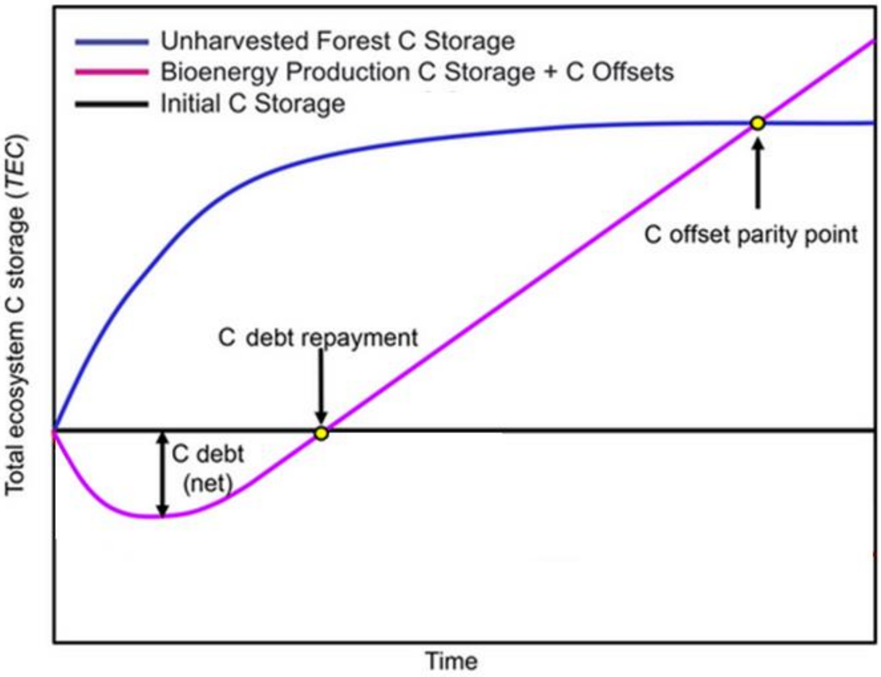


Figure 3. *(From: Mitchell et al., 2012) Carbon debt repayment and carbon parity points. The carbon balance (purple line) indicates the system carbon storage (including carbon offsets from replacing fossil fuels) over time. When it reaches its initial value (black line), the carbon debt is repaid. When it reaches the carbon balance of some counterfactual scenario (in this case a non-harvesting scenario – blue line) carbon parity is reached.*

Carbon debt- and parity payback times of bioenergy from wood pellets that have been found in previous literature vary substantially (i.e. from zero years to centuries; see annex I). Reported payback times depend on the studied area and a range of other factors (including the exact scenario assumed, variables considered in the analysis, and methodological choices). Annex I provides an overview of these factors and the carbon payback times found in previous studies. To date, the following factors have been shown to strongly influence the carbon balance and/or payback times of wood pellet used for bioenergy:

- Initial land-use change (LUC); a higher LUC-associated carbon debt leads to longer payback times (e.g. Schlamadinger & Marland, 1996a; Marland & Schlamadinger, 1997; Holtsmark, 2010, 2012a, 2012b; Pinchot Institute, 2013).

---

[8] This can either be the carbon debt repayment point or carbon parity point depending on whether a counterfactual scenario is assumed or not. Note that this is point does *not* indicate carbon neutrality, but merely to a situation where the bioenergy option emits just as much carbon as the fossil reference system. Carbon neutrality is further discussed in section 2.1

- Average carbon stocks of the production forest, as affected by harvesting frequency and intensity, as well as methodological modelling approach[9]. Lower harvesting frequency and intensity lead to higher average carbon stocks, but lower avoided emissions through replacing fossil fuels (Holtsmark, 2010, 2012a, 2012b; Walker et al., 2010; Mitchell et al., 2012; Zanchi et al., 2012; Lamers et al., 2013a). A stand level approach leads to longer payback times compared to a landscape level approach (Jonker et al., 2013).
- Wood pellet feedstock type (roundwood, mill residues, etc.); if a feedstock material causes GHG emissions in the short term when not used for wood pellet production (e.g. because it would quickly decompose or be burnt as waste), using it to produce pellets results in short carbon parity payback times or even instant carbon benefits (i.e. a carbon payback time of zero years) (McKechnie et al., 2011; Zanchi et al., 2012; Agostini et al., 2013; Bernier & Paré, 2013; Lamers et al., 2013a, 2014b; Stephenson & MacKay, 2014).
- Tree growth rate, which in turn depends biome/region, species and forest management; higher growth rates result in short carbon payback times (Schlamadinger & Marland, 1996a; Marland & Schlamadinger, 1997; Cherubini et al., 2011a; Colnes et al., 2012; Mitchell et al., 2012; Zanchi et al., 2012; Jonker et al., 2013; Lamers et al., 2013a, 2014b).
- The allocation of feedstock over different end-uses (bioenergy, pulp & paper, timber); allocations can reduce the carbon debt of wood pellets used for bioenergy, depending on the type of allocation (Schlamadinger & Marland, 1996a; Lamers et al., 2014b; discussed by Zanchi et al., 2012).
- The carbon efficiency of the value chain[10]; a higher value chain efficiency decreases carbon payback times (Schlamadinger & Marland, 1996a; Marland & Schlamadinger, 1997; Cherubini et al., 2009; McKechnie et al., 2011; Colnes et al., 2012; Mitchell et al., 2012; Jonker et al., 2013).
- The fossil fuel replaced; higher GHG intensity of the fossil fuel replaced leads to shorter carbon payback times; coal has the higest GHG intensity followed by oil and natural gas (Cherubini et al., 2009; Walker et al., 2010; Sikkema et al., 2011; McKechnie et al., 2011; Colnes et al., 2012; Zanchi et al., 2012; Jonker et al., 2013; Lamers et al., 2013).
- The counterfactual scenario assumed (relevant for carbon *parity* payback times only); higher (net) GHG emissions in the counterfactual scenario lead to shorter carbon parity payback times (Marland & Schlamadinger, 1997; Walker et al., 2010; Zanchi et al., 2012; Jonker et al., 2013; Lamers et al., 2013a, 2014b; Stephenson & MacKay, 2014).

There are other, more complex factors that could influence the carbon balance – or in a wider sense the climate mitigation potential - of wood pellet bioenergy, but that are less studied or well-understood; they include:

- Market-driven indirect emissions (through indirect land use change [iLUC][11] and wood use change [iWUC][11]; Agostini et al., 2013)
- Indirect climate forcers, including albedo change, impulse response functions (IRFs)[12], and impacts on aerosol and tropospheric ozone formation (Agostini et al., 2013; Pinchot Institute,

---

[9] The methodological approach is either a *single stand level approach* (carbon dynamics of one forest plot are modelled from planting to harvesting, biomass increases throughout the rotation period) or a *landscape level approach* (carbon dynamics of the forest landscape as a whole are modelled, multiple plots are considered with age-classes ranging from just planted up in one-year steps to plots that are ready for harvest, resulting in constant biomass levels) (see Jonker et al., 2013; Lamers et al., 2013a).

[10] The wood pellet value chain comprises the entire route from producing biomass to replacing fossil fuels and all the forest management-, allocation-, processing- and transport steps in between.

[11] Indirect land use change (iLUC): LUC in one area may affect LUC of another (e.g. bioenergy crops replace food crops, which is compensated for by clearing forests for new agricultural land elsewhere). Similarly, wood use for wood pellets could increase tree harvesting elsewhere: indirect wood use change (iWUC).

[12] Impulse response functions account for the net climate impact of GHG that are temporarily in the atmosphere, e.g. until carbon debt payback.

2013; Cherubini et al., 2011b, 2012a). The effect of IRFs is likely to be limited (Holtsmark, 2012a).
- Changes in soil carbon stocks associated with LUC or harvesting. Soil carbon dynamics are complex and difficult to model; many uncertainties remain (Lamers et al., 2013a).
- The exact effect of biophysical factors underlying growth (including temperature, rain, elevation, irradiation and soil quality) on carbon payback times of wood pellets used for bioelectricity. Growth may be modelled using physiologically-detailed growth models (see for example Landsberg & Waring, 1997; Bryars et al., 2013; Burkhart et al., 2001).

As stated above, wood pellet feedstock type (e.g. saw mill residues, roundwood, etc.) can strongly influence carbon payback times of wood pellet bioenergy (McKechnie et al., 2011; Zanchi et al., 2012; Bernier & Paré, 2013; Lamers et al., 2013a, 2014b). However, the influence of feedstock type on carbon payback times has not been investigated for bioenergy from wood pellets (and their feedstocks) originating from the US South-East. Feedstock type affects the size of the carbon debt of wood pellet bioenergy (Lamers et al., 2013a). Moreover, feedstock type is especially relevant, because it determines what counterfactual scenarios should be considered, which in turn has a large impact on carbon parity payback times of wood pellets used for bioenergy.

Traditionally, wood pellet mills in the US South-East produced wood pellets using saw mill residues as feedstock (A. Taylor, personal communication, April 10, 2015). When saw mill residue supply declined due to the 2008-2009 recession, pellet mills started using roundwood and other non-mill residue materials pellet feedstock (Spelter & Toth, 2009; Buchholz & Gunn, 2015), including forest harvesting residues and whole trees (Wear & Greis, 2013; Dwivedi et al., 2014; Buchholz & Gunn, 2015; NRDC, 2015; Thiffault et al., 2015). Currently, what exact (mix of) feedstocks is ultimately used in a specifc wood pellet plant depends on local markets (B. Abt, personal communication, May 27, 2015) and the wood pellet plant's set-up and capacity to process different feedstocks.

Beside the exact type of feedstock, the type of tree (from which wood pellet feedstock originates) may also affect the carbon payback times of wood pellet bioenergy. This has not been investigated for wood pellets from the US South-East, or any other region – to the author's knowledge. The most commonly used distinction of tree types is between hardwoods (broadleaved tree species) and softwoods (conifers – in the US South-East mostly pine, including from plantations), which are both used to produce wood pellets in the US South-East (Spelter & Toth, 2009; tree definitions obtained from Oxford dictionary of English).

A third, more subjective factor that may strongly influence carbon payback times and has not been investigated before is the *temporal pespective* assumed in the analysis of payback times of wood pellet bioenergy. The temporal perspective refers to what time point in time is chosen to determine the reference amount of carbon stored in the system. There are two main views on this[13], reference carbon stocks are determined: 1) just before harvesting trees, or 2), when trees start growing. The reasoning behind these two different temporal perspectives is further outlined in box 2. The perspectives result in different ways of carbon accounting, but how this affects carbon payback times of wood pellet bioenergy has not been studied. Confirming the issue of these divided views, albeit in a more general sense, recent papers stress the need for common accounting principles (on both sides of the Atlantic) to accurately account for greenhouse gas emissions of bioenergy (Buchholz et al., 2015; Galik & Abt, 2015), referring to it as a "critical policy decision" (Galik & Abt, 2015) that could also strongly influence wood consumption (Prestemon et al., 2015).

---

[13] There are supporters of both perspectives on both sides of the Atlantic. Views on this matter somtimes also reflect a wider issue of whether parties are against or in favour of wood pellet bioenergy (see box 2).

Box 2. Temporal perspectives on the reference amount of carbon

There are two main temporal perspectives with respect to when the reference amount of carbon in the system should be determined. Arguments for both views and examples of their use in previous work are outlined in the two subsections below.

Temporal perspective 1: reference carbon is determined just before harvesting

Most recent studies on the carbon payback times of wood pelles used for bioenergy take the carbon stocks just before harvesting as a reference point; hence they assume that harvesting reduces the carbon stock via a harvest-related carbon debt (e.g. Mitchell et al., 2012; Jonker et al. 2013; Lamers et al., 2013a; Lamers et al., 2014b), or via a similar mechanism that is not specifically referred to as a carbon debt (McKechnie et al. 2011[14]; NRDC, 2015[15]). In line with convention in recent research, it makes sense to take the carbon stock just before harvesting as a reference.

A more explanatory argument for determining the reference amount of carbon in the system just before harvesting can be derived from the research by Searchinger and colleagues. Their main point is that in most cases biomass would have grown and taken up carbon regardless of whether it is used for bioenergy or not[16] (Searchinger et al., 2009; Seachinger 2010; Searchinger at KNAW, 2015). When it is assumed that the stored carbon in biomass would have been there anyway, it makes sense to take the moment just before harvesting as a reference point and consider the harvested, extracted carbon a loss in stock.

Based on previous studies this first temporal perspective can be methodologically approached by determining a (harvest-related) carbon debt and the subsequent regrowth rate of the forest, as is further explained in chapter 2. Even when harvest residues or mill residues are used to produce wood pellets the (additional- in case of harvest residues) carbon that is extracted from the environment can be considered a debt (similar to the approach by McKechnie et al., 2011[14]). This formed a part of the analysis of this study (see section 2.2).

Temporal perspective 2: reference carbon is determined when trees start growth

Shifting the reference situation to the moment that trees strart growing reverses the reasoning: forest biomass sequesters carbon during growth, so harvesting this biomass can never decrease carbon storage of the land below the reference situation, and hence never causes a (harvest-related) carbon debt. The question then arises whether forests would have grown on this land anyway (as assumed by Searchinger et al., 2009; Seachinger 2010; Searchinger at KNAW, 2015), which would mean that shifting the temporal perspective in this way presents a distorted picture, or whether forests are maintained or even planted, (partly) *because* they are later harvested. There is evidence that supports the latter in the US South-East: Firstly, there is a historic correlation between increases in forest harvests and increases in forest inventory (Smith et al., 2007). Secondly, two forest economics model studies show that demand for wood pellet feedstock *in itself* has a stimulating effect on total forest area in the US South-East (Abt et al., 2014; Galik & Abt, 2015). These results do not mean that total forest area is expected to increase in the coming decades (in fact it will decrease somewhat as explained in box 1). However, these results do imply that demand for forest products and for pellets specifically may drive and conserve forested land use, as was also found in a recent review by Miner et al. (2014).

---

[14] McKechnie et al. (2011) allocate changes in the forest's carbon stocks due to additional biomass extraction to produce bioenergy to this bioenergy (this in fact similar to carbon debt as defined in this study, see chapter 3).

[15] In the NRDC (2015) model study carbon is emitted through burning biomass and forest regrowth eventually resequesters the emitted carbon, the authors note that this outcome is similar to carbon debt studies.

[16] This is one of the points made by Searchinger and colleagues against the use of bioenergy in general; two of their main conclusions based on this rationale is that bioenergy only reduces carbon emissions, if 1) it leads to *additional* biomass growth and carbon uptake, or 2) residual biomass is used, which would have been burned or have decomposed anyway (Searchinger et al., 2009; Seachinger 2010; Searchinger at KNAW, 2015).

box 2 continued

This second temporal perspective can be considered by not assigning a harvest-related carbon debt to extracted biomass and not modelling its subsequent regrowth (see chapter 2), as all carbon in biomass is already “paid for” during its growth, or put differently: because biogenic carbon is considered carbon neutral. A different, unrelated reason for not considering a harvest-related carbon debt for wood pellet feedstocks is that the decision to harvest is often driven by other, higher value products, notably saw logs (Emory, B., personal communication, May 29, 2015) and is less likely to be driven by (European) demand for wood pellets and its resulting demand for wood pellet feedstock (V. Dale & K. Kline, personal communication, May 28 2015). The underlying assumption seems to be that even if there is a harvesting-related carbon debt, it should not be allocated to wood pellets.

This study aims to increase understanding of how carbon debt and parity payback times of electricity that is generated in the Netherlands using wood pellets from the south-eastern US are affected by the choice of wood pellet feedstock. For a more comprehensive analysis the effects of tree type and the temporal perspective (i.e. at what point time the reference amount of carbon is determined) are investigated as well. The first and main research questions is: (1) How do carbon debt and parity payback times of biolelecitricity generated in the Netherlands using wood pellets from the south-eastern US vary depending on wood pellet feedstock type? Further research questions are: (2) How does tree type (softwood/hardwood) influence carbon payback times of biolelecitricity generated in the Netherlands using wood pellets from the south-eastern US? and (3) How does the assumed temporal perspective on determining reference carbon stocks affect carbon debt and parity payback times of biolelecitricity generated in the Netherlands using wood pellets from the south-eastern US?

Carbon payback times calculations in this study include the effect of non-CO_2 greenhouse gases. Payback times are expressed per amount of electricity produced, enabling fair comparison of different wood pellet feedstocks. This study focuses on harvest-related carbon debt. Effects of LUC, iLUC[17], iWUC[17] on carbon payback times are not included as is further explained in the method chapter.

---

[17] Indirect land use change (iLUC): LUC in one area may affect LUC of another (e.g. bioenergy crops replace food crops, which is compensated for by clearing forests for new agricultural land elsewhere). Similarly, wood use for wood pellets could increase tree harvesting elsewhere: indirect wood use change (iWUC).

2. Methods

This study compared carbon payback times of bioelectricity that is generated using wood pellets from different feedstock types, looking specifically at wood pellets from the south-eastern United States that are co-fired in a Dutch coal-fired power plant. A total of four feedstock categories (section 2.1), two tree types (hardwood/softwood), two temporal perspectives (box 2 and below) and a range of counterfactual scenarios (section 2.5) were considered. Both carbon debt payback times and carbon parity payback times were determined.

Research overview

This study was conducted in eight steps (see figure 4). Step numbers correspond with sections 2.1 through 2.8, in which each step is explained in detail. The first step was to accurately define eight wood pellet feedstock types studied here, based on feedstock category and tree type (see section 2.1). Then, to ultimately determine carbon *debt* payback times of wood pellets (section 2.7) three components of the wood pellet carbon balance were required (see figure 4): the harvest-associated carbon debt of the different feedstock types (section 2.2), the carbon sequestration rate through forest regrowth (section 2.3), and the net avoided carbon emissions[18] via the use of wood pellets for bioelectricity (section 2.4)[19]. The debt payback time was then determined by subtracting net avoided emissions from the harvest-associated carbon debt, and calculating the time until carbon sequestration through forest regrowth fully compensated the remaining debt (see formula 1 and condition 2, for details see section 2.7).

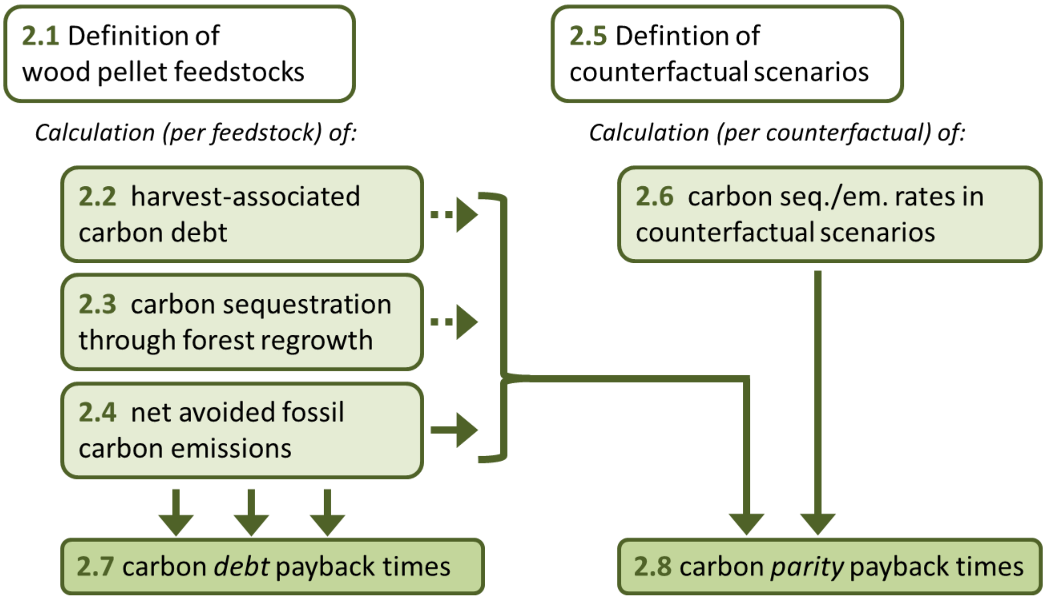


Figure 4. *Research overview: Wood pellet feedstock types and their counterfactual scenarios were defined in section 2.1 and 2.5 respectively (no shading). Sections 2.2-2.4 and 2.6 (light shaded) form the core of the research and allow calculations of carbon debt and parity payback times (sections 2.7 and 2.8 respectively; dark shaded). Dotted arrows indicate that the particular flow of information is not always required (see text on temporal perspectives and on thinnings). Abbreviations: seq. = sequestration; em. = emission.*

---

[18] Avoided fossil emissions are emissions from burning fossil fuels that are no longer produced when an alternative energy source (in this case biomass) replaces fossil fuels.

[19] Carbon debt and forest regrowth concern biogenic carbon (see sections 2.2 and 2.3); net avoided emissions concern fossil fuel and land-use emissions (see section 2.4).

$$CB1_i = -CD + NAE + CS_i \tag{1}$$

$$carbon\ debt\ payback\ time\colon\ year\ i\ for\ which\ CB_i = 0 \tag{2}$$

Where:

$CB1_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the first temporal perspective (tonne carbon / MWh)

CD = harvest-associated carbon debt (tonne carbon / MWh)

NAE = net avoided fossil carbon emissions in year i (tonne carbon / MWh)

CS_i = cumulative carbon sequestration (tonne carbon / MWh)

i = year after harvesting

Carbon parity payback times are based on some counterfactual scenario (see figure 4; see section introduction for a description of the counterfactual scenario concept). The first step in determining parity payback times was therefore to define counterfactual scenarios for each feedstock type (section 2.5). Next, the net carbon effect of these counterfactual scenarios was determined, i.e. their net carbon sequestration or emission rate (section 2.6). Lastly, the carbon parity payback time was calculated by again subtracting net avoided emissions from the carbon debt, but then determining at what point in time carbon sequestration (through forest regrowth; starting from the remaining carbon debt) equals the carbon effect of the counterfactual scenario (see formula 1 and condition 4, for details on the methodology used here see section 2.8).

$$CB1_i = -CD + NAE + CS_i \tag{1}$$

$$CB2_i = NAE \tag{3}$$

$$carbon\ parity\ payback\ time\colon\ year\ i\ for\ which\ CB1_i = CC1_i \tag{4}$$

$$carbon\ parity\ payback\ time\colon\ year\ i\ for\ which\ CB2_i = CC2_i \tag{5}$$

Where:

$CB1_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the first temporal perspective (tonne carbon / MWh)

$CB2_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the second temporal perspective and/or when using thinnings as feedstock (tonne carbon / MWh)

CD = cumulative[20] harvest-associated carbon debt (in tonne carbon / MWh)

NAE = cumulative[20] net avoided fossil carbon emissions (tonne carbon / MWh)

CS_i = cumulative carbon sequestration in year i (tonne carbon / MWh)

$CC1_i$ = net cumulative carbon emission or sequestration in the counterfactual scenario in year i assuming the first temporal perspective (tonne carbon / MWh)

$CC2_i$ = net cumulative carbon emission or sequestration in the counterfactual scenario in year i assuming the second temporal perspective and/ or when considering thinnings (tonne carbon / MWh)

i = year after (what would be) harvesting for wood pellet production in the factual scenario

---

[20] Cumulative CD or NAE means that after each harvest a new CD and NAE were added to the carbon balance.

The temporal perspective (see box 2) was analysed in this study in the following way: When the first temporal perspective (reference carbon stock determined just before harvesting) was assumed, the analysis was performed as described above. However, when the second temporal perspective (reference carbon stock determined when tree growth starts) was assumed two adjustments were made. First, no (harvest-associated) carbon debt was considered, as the final harvest does not reduce carbon stocks below the reference is not in this perspective. Secondly, no carbon sequestration through forest regrowth was considered, as any sequestration after harvesting would under this view be attributable to the next harvest (put differently: sequestration is already allocated to the *next* harvest). These adjustments are intrinsic consequences of the second perspective (see also box 2). Therefore, when using this second perspective, no carbon *debt* payback times had to be calculated (as debt payback times would always be zero years) and the carbon *parity* payback time was based on avoided emissions and the counterfactual scenario only (see figure 4, dotted arrows do not hold in the second perspective; see formula 3 and condition 5). As further explained in section 2.1, the same two adjustments were made for the thinning feedstock category in general (regardless of temporal perspective), but for different reasons.

Methodological approach

In contrast to most studies on the carbon balance of wood pellets, it was decided not to use a carbon accounting model (CAM) in this research (for an overview of these studies and their CAMs, see annex I; for a description of commonly used CAMs see annex II). The reason being that carbon accounting models, while usually giving a broad overview of carbon in different natural and man-made carbon pools and the dynamics between these pools, can mask underlying assumptions and drivers of the final results. Here, the research was performed following the steps in figure 4. Assumptions and formulas were all explicitly defined for each step, allowing insight and discussion. In these steps, the dynamics of the forestry system and subsequent value chains (including forest growth, temporal perspectives, carbon debt, value chain emissions, avoided emissions and counterfactual scenarios) were reduced to their relevance for the carbon balance of wood pellets specifically. Key carbon dynamics were then summarised in final payback time calculations (section 2.7 and 2.8). This approach led to a simpler and comprehensible representation of the system of using wood pellets for bioelectricity, while strongly drawing from previous (empirical and model) studies and local expert knowledge to maintain realism, yielding a simplified carbon accounting model.

The physical quantity studied in this research was the s*ystem carbon effect*: the changes in the system's carbon storage over time. This quantity can describe both the carbon balance of producing bioelectricity from wood pellets and counterfactual scenarios. The system consisted of ecosystem carbon stocks, carbon in man-made products and avoided fossil carbon emissions. Carbon stocks and flows were calculated per amount of electricity produced from wood pellets. Carbon stocks were expressed as tonne carbon / MWh[21]. Carbon flows (emission/sequestration) were expressed as tonne carbon / MWh in a certain year (i.e. tC MWh^{-1} yr^{-1}). This approach is comparable to a single stand approach (see footnote 9), but instead of focusing on the carbon balance of a hectare of forested land, the carbon balance of an amount electricity from wood pellets produced was considered. This method and unit provided the most accurate and fairest way to compare the system carbon effect of wood pellets from different feedstocks and under different temporal perspectives, as it focused on the final output – in this case electricity, similar to a functional unit in life-cycle assessment.

Other than the specific assumptions made per research step (see section 2.1 through 2.8), four general assumptions were made in this research. Firstly, as mentioned in the introduction effects

---

[21] MWh (megawatt hour) is 3.6 billion Joules of (electric) energy. Electricity is higher quality energy (i.e. has a higher exergetic content) than for instance heat. Here a MWh only refers to the (fraction of total) electricity that is produced from wood pellets.

of land-use change (LUC), indirect LUC (iLUC) and indirect wood use change (iWUC)[22] were not included in this study. LUC is a factor that can strongly influence payback times (Schlamadinger & Marland, 1996a; Marland & Schlamadinger, 1997; Holtsmark, 2010, 2012a, 2012b; Pinchot Institute, 2013) and occurs in the US South-East. However, most forested land in the US South-East has been forested for over 70 years and maximum expected losses in forest acreage by the year 2060 are 13% (Wear & Greis, 2013; see box 1). In many cases LUC will not be a relevant factor and was considered beyond the scope of this study; therefore only the harvest-related carbon debt was part of the calculations of this study. Both indirect land use change (iLUC) and indirect wood use change (iWUC) can also influence carbon payback times of wood pellet bioenergy (Agostini et al., 2013) and occur in the US South-East. However, the decreased local demand for pulp and paper products (Wear & Greis, 2013), may allow bioenergy to develop without drastically increasing land or wood requirements. It was decided not to include any iLUC or iWUC effects (as was for instance also assumed by Jonker et al., 2013; further discussed in chapter 4).

Secondly, in the analyses of this study the year zero was always set at the moment the feedstock was harvested; this is independent of the temporal perspective assumed (which was already fully accounted for, see the final paragraph of the previous subsection, page 12). This assumption also holds for thinnings – the next thinning was assumed to occur one rotation period later resulting in the same frequency of feedstock harvesting, and for mill residues, which were assumed to be produced and used for wood pellet manufacturing directly after harvesting (i.e. in year zero).

Thirdly, the wood pellet value chain assumed in this study was analysed in its entirety, the value chain was based on previous literature[23]: wood pellet feedstock is grown, harvested and transported (by truck) to a pellet mill, where wood pellets are produced (all in the US South-East), pellets are transported (by truck or train) to the nearest main seaport, shipped across the Atlantic to Rotterdam, and transported (truck or barge) to the Dutch coal-fired power plant at Geertruidenberg[24], where they are co-fired, replacing hard coal. All processing and transport was assumed to be fossil fuel-driven. The wood pellet side-product of tree bark was accounted for via additional avoided emissions (for reasons described in section 2.2).

Fourthly, all allocation steps were based on carbon content. As an example, the (harvest-associated) carbon debt of wood pellet-based bioelectricity was predominantly based on the carbon content of the wood pellet feedstock, as it represented the carbon extracted from the environment (see section 2.2). As a result of this assumption the main differences among feedstocks were defined in their counterfactuals (e.g. what is the main difference between harvest residues and roundwood in terms of carbon? Not their carbon content, but rather the fact that residues would have had different uses than roundwood, had they not been used for wood pellet production).

Carbon balance and greenhouse gas balance

A final methodological consideration is the difference between greenhouse gas (GHG) balances and carbon balances. This study looked at the carbon balance of the system of using wood pellets for

---

[22] Indirect land use change (iLUC): LUC in one area may affect LUC of another (e.g. bioenergy crops replace food crops, which is compensated for by clearing forests for new agricultural land elsewhere). Similarly, wood use for wood pellets could increase tree harvesting elsewhere: indirect wood use change (iWUC).

[23] The value chain was predominantly based on: Dwivedi et al., 2011; Jonker et al., 2013; as well as: Sikkema et al., 2010; Dwivedi et al., 2014; and to a lesser extent: Cherubini et al., 2009; Magelli et al., 2009. For details on the value chain and detailed references see sections 2.2 (relating to carbon debt) and 2.4 (relating to fossil emissions).

[24] In 2011 *RWE Essent*'s coal and biomass co-fired power plant at Geertruidenberg (known in the Netherlands as: de Amercentrale) was by far largest consumer of wood pellets in the Netherlands (SOMO, 2013), using more than four times more pellets than all other utilities combined. By 2013, the Amercentrale was the only power plant in the Netherlands that used wood pellets (Junginger, personal communication, June 16, 2015). It was therefore decided to base calculations of this study on this plant. In previous work by Sikkema et al. (2010) on the carbon balance of wood pellets used to produce bioelectricity, pellet to electricity conversion efficiency and carbon emissions of transport to the plant were already identified for this plant.

bioelectricity. The system was approached as different carbon stocks (ecosystem, man-made materials, avoided emissions) and carbon in the form of CO_2 that is emitted to- and sequestered from the atmosphere. The ultimate goal of looking at carbon balances and calculating carbon payback times is to gain insights into the climate benefits of a system. Greenhouse gases (GHGs) other than CO_2, notably methane (CH_4) and nitrous oxide (N_2O), should thus also be considered (IPCC, 2013; Cherubini et al., 2009)[25]. However, including other GHGs distorts the (mass) balance of carbon (as some other GHG do no consist of carbon or have different global warming potentials[25]). Fortunately, the difference between carbon and GHG analysis is only relevant for a few aspects of this study. The carbon balance here was therefore based on stored carbon and primarily on carbon in CO_2. Where the impact of non-CO_2 GHGs was relevant and significant, specific assumptions were made and the effect of these other GHGs was included (see final two paragraphs of this subsection). For the analysis as a whole, this means that the total GHG effect was accounted for; the *system carbon effect* (as described above) thus includes the effect of greenhouse gases other than CO_2 as well.

The following three paragraphs set out the aspects of this study where differentiating between a CO_2 based carbon balance and a GHG balance was not required; exceptions that remain and where all GHGs were considered are listed in the final two paragraphs of this subsection.

First, when looking at carbon storage (carbon in biomass or man-made products) it is irrelevant whether CO_2 or all GHGs are considered, as neither are involved in the storage itself. GHGs other than CO_2 are also not involved in the carbon sequestration flow (CO_2 uptake). For these two processes the difference between looking at CO_2 only or at all GHGs is irrelevant.

Secondly, for avoided fossil emissions, i.e. the emissions of (no longer) burning fossil fuels, the difference between CO_2 emissions and total GHG emissions (CO_2-equivalent emissions) was found to be (very) limited: Non-CO_2 GHG emissions from stationary fossil fuel combustion only contribute a small share of total GHG emissions (looking at the global warming potential over 100 years [GWP_{100}-weighted][25]):0.2- 0.7% for coal (0.7% for hard coal, which is used at the plant considered in this study), 0.3% for oil and 0.1%-0.6% for natural gas (based on EPA 2014, WDNR, 2010 and GWP_{100} values from IPCC, 2013). Because of these minimal shares of other GHGs and the fact the differences between CO_2 only and GHGs were covered by the parameter variation for the sensitivity analysis, it was conisdered valid to only use CO_2 emissions for avoided emissions.

Thirdly, when looking at the carbon debt, the full greenhouse gas effect of burning wood pellets could be considered part of the debt. The GWP_{100}-weighted shares of non-CO_2 GHG in total emissions of combusting wood and wood products (including wood pellets and bark) are 1.2-1.9% (WDNR,2010; EPA, 2014; IPCC, 2013) – again a limited share. Based on these percantages the carbon debt could be increased by a factor [1/98.1] to [1/0.98.8], but this complicates accounting significantly. Moreover, this small increase was more than covered by the large variation already assumed for the sensitivity analysis of the carbon debt (see section 2.2), the increase was therefore not included in the analysis of this study.

Greenhouse gas emissions along the wood pellet value chain (forest management, harvesting, transport, processing, etc.) can have a significant non-CO_2 component. This often holds in particular for: 1) forest management, due to N_2O emissions from fertilisers[26] (e.g. Jonker et al., 2013; Dwivedi et al., 2014), and 2) wood pellet production (Magelli et al., 2009), due to CH_4 from natural gas use (potentially via leaks or incomplete combustion), as well as 3) emissions from shipping (e.g. Magelli et

---

[25] Apart from CO_2, methane (CH_4) and nitrous oxide (N_2O) are *by far* the most important anthropogenic greenhouse gases, both globally (IPCC, 2013) and for bioenergy production specifically (Cherubini et al., 2009). The global warming potential over a period of 100 years (GWP_{100}) of these three gases is expressed in CO_2-equivalents. CO_2 by definition has a GWP_{100} of one, CH_4 a GWP_{100} of 28 (assuming no climate feedbacks) and N_2O a GWP_{100} of 265 CO_2-equivalents (again assuming no climate feedbacks; IPCC, 2013). This means that for instance one molecule CH_4 has the same climate effect (via enhanced radiative forcing) over the course of a hundred years as 28 molecules of CO_2 (IPCC, 2013).

[26] Note that fertilisers are only used in intensively managed forests; when forest management intensity is low, non-CO_2 GHG emissions can be close to zero (based on Jonker et al., 2013; Dwivedi et al., 2014). No distinction based on management intensity was made in the present study.

al., 2009). For other parts of the value chain the difference between CO_2 and CO_2-equivalent emissions is smaller[27] (see example footnote and Magelli et al., 2009). However, the wood pellet value chain was considered in its entirety. Value chain emissions were therefore determined as GHG emissions in general, rather than as CO_2 only. .

Some counterfactual scenarios include significant non-CO_2 GHG emissions, these were accounted for as described in section 2.6 They include methane emissions from landfilled forest products[28] (part counterfactuals 1a, 2a and 4a), and non-CO_2 GHG emissions (in general) from burning harvest residues and mill residues (part of counterfactual 3b, 3c and 4b).

Minimum/maximum- analysis & Sensitivity analysis

For all parameters of this research's four main components (harvest-associated carbon debt, net avoided emissions, biomass regeneration and the counterfactuals; see light shaded boxes in figure 4) minimum and maximum values were determined alongside the default value, representing the uncertainty that exists with respect to the exact value. In sections 2.2-2.4 and 2.6 (for the four components) the default, minimum and maximum parameter values are tabulated and it is explained how these values were obtained. Using all combinations of the resulting minimum and maximum values for each component, the shortest and longest possible payback times were calculated to cover the entire possible range of payback times. Moreover a sensitivity analysis was performed on the results of this study using the minimum and maximum values of each component. One component was varied at a time from minimum to default to maximum values, and the effect on payback times was determined. Results were graphically presented using spider diagrams (see chapter 3). It was analysed what components have the largest effect on payback times in relative and absolute terms.

---

[27] Transport by trucks for instance has relatively low GWP_{100}-weighted shares of non-CO_2 GHG in total emissions: 1.1% and 0.2% for light- and heavy trucks respectively (EPA, 2014; IPCC, 2013). A similar share may be expected for harvesting equipment.

[28] Landfilled forest products release about 20% of their carbon content as methane (Ingerson, 2010, based on EPA 2006)

2.1 Definition of wood pellet feedstock types

As discussed in the introduction, a range of feedstock types are used to produce wood pellets in the US South-East. Furthermore, wood pellet feedstock can originate from either soft- or hardwood. In this study feedstock types were divided into the four categories listed below[29]; each category was investigated for both soft- and hardwoods.

1) *Low-grade roundwood*: ranging from lowest quality (very small, crooked, diseased, or damaged, i.e. non-merchantable roundwood) up to pulpwood (traditionally used for fiber, e.g. in paper production) size and quality (often either large tops of sawlogs or smaller whole stems). This category excludes thinnings and smaller (non-pulpwood) tops and limbs, and principally represents roundwood in the sense of stem only rather than whole trees[30]. It also excludes higher quality roundwood (above pulpwood-quality) - the majority of which is formed by sawlogs; this higher quality roundwood is used in the timber industry, and is simply too expensive to be used as wood pellet feedstock.
2) *Thinnings*: both pre-commercial[31] (non-merchantable to traditional forest industries, too small) and commercial thinnings (i.e. merchantable to traditional industries- e.g. pulp & paper). Thinnings are made to promote growth of remaining higher quality trees[32].
3) *Mill residues*: sawdust and shavings from other mill types (predominantly saw mills). Though sawdust and shavings are often partially or entirely used internally or used at other mill types (usually paper mills), pellet mills also use these mill residues as a feedstock.
4) *Harvest residues*: tops and limbs, slash, waste wood and woody debris left after harvesting. The terminology is not very strict and these terms partially overlap (e.g. tops and limbs may be considered waste wood). However, this category includes all material that would be left after harvesting in traditional forestry (i.e. harvesting for traditional forest products). It must be noted that not all harvest residues are suitable for pellet production (this is accounted for in step 2).

   So-called *in-wood chips* form another type of wood pellet feedstock, these chips themselves can be made from different materials and are defined only by the fact that they are produced in the forest using a chipper.. In this study it is maintained that when in-wood chips are produced from harvest residues, they fall into the harvest residue category. When low-quality roundwood is already chipped in the forests (as some foresters practice), the in-wood chips fall into the low-quality roundwood category in this study.

This categorisation was based on a survey held among various forest and wood pellet stakeholders and experts, in which it was asked what feedstock materials are used to produce wood pellets in the US South-East (see annex III). Stakeholders and experts surveyed included: representatives of the 25 wood pellet mills that are currently (to the author's knowledge) operating in the US South-East (representatives of eleven mills responded), experts from the two largest corporate foresters in the US, scientists at universities and research institutes in the US South-East, a local environmental NGO and lastly, (informally) colleagues at Utrecht University (see annex III for the full list of respondents).

---

[29] These four categories are from hereon also referred to as simply *feedstock types*.

[30] Though calculations in further research steps are based on stem-only roundwood, results for whole tree harvests would probably be most similar to this first feedstock category, as the majority of the usable biomass in a whole tree is formed by the stem.

[31] From a survey held among wood pellet stakeholders and experts (see annex II) it came forward that pre-commercial thinning is not widespread in the US South-East according to a representative from a pellet mill, but that pre-commercial thinnings are used for pellet production according to other experts (V. Dale & K. Kline).

[32] On plantations, trees may be planted at high density to increase revenue from thinning harvests (M. Junginger, personal communication, March, 2015)

All included feedstock types have also been identified in previous studies on wood pellets in the US South-East (Dwivedi et al., 2014; Stephenson & MacKay, 2014; Buchholz & Gunn, 2015; NRDC, 2015)[33] as well as in other regions[34].Most of these studies do not look at all feedstocks at once and their feedstock categorisation differs somewhat, though the categorisation made in a recent study by the NRDC (2015) is similar to the one used here.

Based on the aforementioned survey, estimates were made of the relative shares of different feedstock categories used in pellet mills that specifically export to the Netherlands. Commercial thinnings (usually pine) were estimated to form over 50% of wood pellet feedstock. Roundwood – again often pine, of pulpwood quality – accounts for about 40% of pellet feedstock. Softwood mill residues and hardwood harvest residues form the remainig feedstocks, at about 2% of the total feedstock each[35]. What can be observed from this distribution is that not all eight feedstock categories are used at these specific mills. However, calculations were made for all eight categories to give a more complete overview and enable wider conclusions.

Assumption for the methodological approach for thinnings as wood pellet feedstock

For the thinnings feedstock category a specific assumption was made. The thinnings' carbon debt incurred during their harvest is assumed to be compensated for via enhanced forest growth after thinning. Therefore, at the time of the final harvest, thinning has lowered neither the amount of biomass (and carbon) that can be harvested nor the amount that would remain in the forest (enhanced growth also compensates for decomposition of thinning-related harvest residues). Methodologically, this assumption was implemented by not assigning a carbon debt (section 2.2) or carbon sequestration via forest regrowth (section 2.3) to thinnings used for wood pellet production. This approach was the same regardless of the temporal perspective considered (taking the reference carbon stock at the beginning of tree growth or just before harvesting). The approach also affects the counterfactual scenario calculations, as further explained in section 2.6.

This assumption was based on several previous studies that found that thinning ultimately leads to similar, larger or only slightly reduced carbon stocks before the final harvest. One empirical study reported increased carbon stocks due to thinnings in hardwood forests in the US South-East (Keyser et al., 2012); another empirical study showed that depending on the type of thinning final carbon sequestration can both increase or decrease (Hoover & Stout, 2007). One model study calculated increased carbon stocks due to thinning in south-eastern softwood forests (Jonker et al., 2013) and two other model studies found thinning only causes a slight reduction in final carbon stocks (Gonzalez-Benecke et al., 2010, 2011). Similar results were found in other regions: one empirical and three model studies found increased carbon stocks (Horner et al., 2010; Garcia-Gonzalo 2007a, 2007b; Lindgren & Sullivan, 2013; respectively). Four empirical studies and one model study found that carbon stocks before the final harvest are roughly the same, regardless of whether stands are thinned or not (Mund et al., 2002; Chiang et al., 2008; Powers et al., 2012; Saunders et al., 2012; Pohjola &

---

[33] These studies looked at the carbon balance of wood pellet bioenergy on one way or another, but did not explicitly calculate carbon payback times.

[34] Wood pellet feedstock types used in regions other than the US South-East include mill residues (Sikkema et al., 2010; Lamers et al., 2014b; Stephenson & MacKay, 2014), harvest residues (also known as logging residues or slash; Repo et al., 2010, 2011; Dwivedi et al., 2011; Bernier & Paré, 2013; McKechnie et al., 2011; Zanchi et al., 2012; Lamers et al., 2014b; Stephenson & MacKay, 2014), salvage wood (wood killed by for instance insect infestation or windfall; Lamers et al., 2014b) and forest thinnings, roundwood or whole trees (Holtsmark, 2010, 2012b; Dwivedi et al., 2011, 2014; McKechnie et al., 2011; Mitchell et al., 2012; Zanchi et al., 2012; Bernier & Paré, 2013; Stephenson & MacKay, 2014). Essentially the same feedstocks, though a different classification was used here: salvage wood was part of low-quality roundwood and thinnings were considered separately.

[35] It must be noted here that this distribution can be very different for other pellet mills, and has also changed over time; with recent large increases in wood pellet demand resulting in more roundwood being used (A. Taylor, personal communication, April 10, 2015). An older distribution of the entire North American wood pellet market shows that mill residues formed the largest feedstock in 2008 (Spelter & Toth, 2009).

Valsta, 2007; respectively). One empirical study showed a limited reduction in final carbon stocks, due to thinning (Jiménez et al., 2011). As a final note, the reason for thinning is usually to improve forest health and produce higher quality roundwood, if any carbon stock losses do occur one could argue these should be attributed to the remaining high-quality roundwood (e.g. saw logs) rather than the thinnings themselves.

2.2 Calculation of the harvest-associated carbon debt

The harvest-associated carbon debt (*from here on referred to as carbon debt*) represents the biogenic carbon that is extracted from the environment, no longer stored and released to atmosphere, due to harvesting and using biomass. Here, the carbon debt only included (biogenic) carbon that is entirely released to atmosphere within the first year and it was assumed that these emissions occur in year zero. Other emissions, which include fossil emissions (during harvesting, and wood pellet production, transport and processing) and emissions in counterfactual scenarios, were accounted for in sections 2.4 and 2.6 respectively. Furthermore, based on carbon allocation, it was assumed that all biogenic carbon that was extracted to ultimately produce feedstock forms that feedstock's carbon debt, regardless of why the carbon was extracted[36]. As explained in the general aspects section at the beginning of this chapter, no carbon debt was determined for thinnings or when considering the second temporal perspective (see also box 2).

In this study wood pellets are used to produce electricity and carbon flows are expressed per MWh. The carbon debts of the different wood pellet feedstock types were therefore calculated by working back along the value chain from the power plant to the forest and determining the amount of carbon extracted per MWh of electricity produced. This was done using the following parameters (further discussed below) and formula 6:

$$CD = PEC \cdot TL \cdot FPE \cdot DB \cdot FCC \qquad (6)$$

Where:

CD = harvest-associated carbon debt (in tonne carbon / MWh)

PEC = wood pellet to electricity conversion effciency (in dry tonne pellets / MWh)

TL = transport losses parameter (in dry tonne pellets that left pellet mill / dry tonne pellets that arrive at the power plant)

FPE = wood pellet production effciency (in wet tonne [debarked] feedstock / dry tonne pellets)

DB = debarking parameter (in wet tonne barked feedstock / wet tonne debarked feedstock)

FCC = carbon content of feedstock (tonne C / wet tonne [bark or] feedstock)

[Terms in brackets are only applicable to some feedstock types, see parameter descriptions below.]

The wood pellet to electricity conversion efficiency (**PEC**; in dry tonne pellets / MWh) was derived from previous literature. Based on the embodied energy value of wood pellets (17.6 GJ LHV) and electricity conversion efficiency of 40.1% (for 10% co-firing of wood pellets at the 1245 MW [see Essent, 2015] Dutch coal-fired power plant, "de Amercentrale"; efficiency was assumed to be LHV[37] based) found by Sikkema et al. (2010) a efficiency value of 0.510 dry tonne pellets / MWh was found. Jonker et al. (2013) estimated that 1.56 tonnes of pellets would yield 3.13 MWh, resulting in a value of 0.498 dry tonne pellets / MWh. Based on the wood pellet tonnage consumed and electrcity produced calculated by Dwivedi et al. (2014, in: tables 2 and 3) for a relatively small (and hence less efficient) 100MW powerplant, a value of 0.614 dry tonne pellets / MWh was derived. A default parameter value of 0.510 dry tonne pellets / MWh was assumed here (see table 1), as this study looked at the same power plant as Sikkema et al. (2010). The maximum value (used in the sensitivity analysis) was 0.498 dry tonne pellets / MWh, based on Jonker et al. (2013). The minimum value was set at 0.557 dry tonne

---

[36] So even if a feedstock is considered a residue (e.g. mill- or harvest residues or for instance pulpwood that is considered 100% by-product by its harvesters), it is still allocated a carbon debt.

[37] Lower heating value (LHV) means that energy consumed by the evaporation of water that is created in the combustion process is accounted for.

pellets / MWh, i.e. the average of values obtained from Sikkema et al. (2010) and Dwivedi et al. (2014). The average was taken -rather than just the value based on Dwivedi et al (2014), as these authors looked at significantly smaller plant (12 times smaller in terms of nominal capacity). Conversion efficiency was assumed to be the same for all feedstock and wood types. This assumption is supported by the fact that Sikkema et al. (2010) and Jonker et al. (2013) found a very similar efficiency while using different feedstocks. Moreover, the main determinant of the efficiency is energetic content of the pellets, which is likely highly similar among feedstock and wood types, as they have a similar chemical composition (ECN, 2015) and moisture content after having been processed into wood pellets.

Based on Sikkema et al. (2010) it was assumed that wood pellet losses during transport and transatlantic shipping were 3%. Jonker et al. (2013) estimated 7% losses for the entire wood pellet value chain. It was assumed that lost pellets release their embodied carbon within the first year[38]. Based on these studies, a default loss percentage of 5% was used resulting in a default transport loss parameter (**TL**) of 1/(1-0.05) (see table 1). Minimum and maximum values were based on 3% and 7% losses (based on Sikkema et al., 2010 and Jonker et al., 2013, respectively; see table 1). Tree type and wood pellet feedstock type were irrelevant for the loss percentage.

The wood pellet production efficiency (**FPE**; in wet tonne [debarked] feedstock / dry tonne pellets) was obtained from two previous studies. Magelli et al., (2009) found that 1.56 tonnes of wet feedstock (in this case mill residues – and hence debarked) were needed to produce one tonne of wood pellets. Sikkema et al. (2010) reported 1.57 tonnes of wet feedstock (again mill residues and hence no bark) are required to produce one tonne of wood pellets. Both studies looked at Canadian wood pellets, but results were assumed to be applicable to the US South-East. As these two studies did not specify what tree type the feedstock originated from, no differentation was made between hard- and softwoods here. Low-quality roundwood and mill residues have similar moisture content (Sikkema et al., 2010), therefore it was assumed that roundwood has the same conversion efficiency from feedstock to pellets as mill residues. The same assumption was made for harvest residues. Based on the aforementioned studies the default parameter value used in this study was 1.565 wet tonne [debarked] feedstock / dry tonne pellets (table 1). This parameter can be determined quite accurately, as observed from the small difference between values found in the two studies used here. Minimum and maximum values were therefore set at 10% from the default value for harvesting residue and mill residue feedstocks (see table 1). For the same reason the minimum value for low-quality roundwood was set at 10%. The maximum value however, was set at 18% above the default value (see table 1), this was done to represent variation that could be caused by alternative accounting methods for unused harvesting residues, this is further explained in the final paragraph of this section.

Some pellet feedstocks are debarked before being processed to pellets. Carbon in bark is extracted from the environment, but in these cases bark is not used to produce wood pellets. The debarking parameter (**DB**) accounts for this. Based on Jenkins et al. (2004) bark foms about 16.5% of *aboveground woody* biomass. The remaining 83.5% is material that roundwood, thinnings and mill residues consist of. From a certain minimum tree size upwards the percentage of bark does not change much with increasing diameter at breast height (DBH): ranging from 18.9% bark at cm 15 cm dbh, to 17.1% at 30cm dbh, to 16% at 80 cm dbh, and 15.5% at 300cm at dbh (based on Jenkins et al., 2004). Using these percentages the default value fot the debarking parameter for low-quality roundwood was therefore 1/0.835, and minimum and maximum values 1/0.845 and 1/0.811 respectively (see table 1). Since Jenkins et al. (2004) present their result for trees in general, no differentatiation between hard- and softwoods was made. Removed bark and its embodied carbon was further dealt with in section 2.4. Thinnings were assumed not to have a carbon debt (see previous section), so were not considered in this research step. Harvest residues are not debarked before the pellet production process, so their debarking parameter value was 1. The wood that mill residues originate from was debarked, however the additional carbon debt through this bark was assumed to

---

[38] Hence they were accounted for via the carbon debt.

be entirely allocated to the primary products made from this wood, and not to the mill *residues.* Mill residues were therefore also given a debarking parameter value of 1.

Average carbon contents (dry-based and ash free) of 50.0% for hardwoods and 51.2% for softwoods (here: pine, fir and spruce) percent were obtained from an ECN database (2015) that is based on a large amount of previous studies[39]. Based on the same database the so-called *as received* (wet-based) carbon content of hardwoods and softwoods was determined[40], yielding 42.9% and 43.2% respectively. Because of the small difference between hard- and softwoods, the as received carbon content of the non-bark fraction of all feedstocks was assumed to be same[41]. The default non-bark carbon content used was 0.430 tonne C / tonne wet feedstock (see table 1). Based on the minimum and maximum dry based and ash free carbon content of hardwood and softwood from the ECN (2015) database, the minimum and maximum *as received* carbon contents were calculated (36.6%, 50.2%, 39.9%, 50.4% respectively); since values were again very similar, the minimum carbon content value for all feedstocks was set at 0.366 and the maximum value at 0.504 tonne C / tonne wet feedstock (see table 1). The as received carbon content of bark (in general) of on average 38.9% was again calculated based on ECN (2015). The 16.5% bark fraction (see above) of extracted roundwood was therefore given an FCC value of 0.389 tonne C / tonne wet bark. Based on the minimum and maximum dry-based carbon content values in the ECN (2015) database and the their conversion to as received carbon content, the minimum and maximum bark carbon contents were set at 0.348 and 0.422 tonne C / tonne wet bark.

Table 1. *Default, minimum and maximum parameter values for carbon debt calculations. Values are the same for hardwood and softwood and for all feedstock categories (where applicable, see text above). Rounded values are displayed for (default value: PEC; all values except unity: TL, FPE and DB).*

Parameter	**PEC**	**TL**	**FPE**	**DB**	**FCC**
Unit	dtp / MWh	dtp_{mill} / dtp_{plant}	wtdf / dtp	wtbf / wtdf	tC / wtbf
Default value	0.510	1.05	1.57	1 or 1.20[a]	0.430 or 0.389[b]
Minimum value	0.498	1.03	1.41	1 or 1.18[a]	0.366 or 0.348[b]
Maximum value	0.557	1.08	1.91	1 or 1.23[a]	0.504 or 0.422[b]

Unit abbreviations: dtp: dry tonne pellets; wtdf: wet tonne debarked feedstock; wtbf: wet tonne barked feedstock; tC: tonne carbon. a) DB parameter value of 1 was always used for mill residues and harvest residues, the remaining DB parameter values were used for low-quality roundwood. b) The first value represents the FCC value of the feedstock (wood), the second value the FCC value of the bark fraction (of low-quality roundwood).

For these calculations three additional (sets of) assumptions were made: Firstly, belowground carbon was assumed to remain constant over time. The same assumption was made in previous studies on carbon balances of wood pellet bioenergy (Holtsmark, 2010, 2012b; Colnes et al., 2012; Jonker et al.,

---

[39] Moreover, these percentages are in line with other previous literature: e.g. 47.1-51.5% carbon content (dry-based) for hard- and softwood chips (Van Loo & Koppejan, 2008), 49.5-51.9 % carbon content (dry-based) for spruce, oak and beech (Demirbas, 2004), 50% carbon content (dry-based) assumed for wood in general (Jonker et al., 2013; Smith et al., 2006).

[40] As received carbon content was calculated based on the formulas used in the ECN database (2015) that define what fractions (moisture, ash, etc.) are contained in as-received vs. dry based.

[41] In literature mill residues are sometimes reported to have slightly higher carbon content, i.e. 46.9-48.3% (Abbas et al., 1994; ECN, 2015). However, the mill residues in these studies were dried and had lower moisture contents, which would lead to higher carbon content.

2013; and[42]). It should be noted though that harvest residues were not removed from the forest in the studies by Colnes et al. (2012) and Jonker et al. (2013) - making net soil carbon loss less likely. However, according to other sources belowground carbon is not strongly affected by harvesting, as long as roots are left in place and trees are allowed to regrow / are replanted (M. Post, personal communication, April 7, 2015; Sullivan et al., 2008 who looked at thinnings specifically; Smith et al., 2006), meaning that belowground carbon can stay roughly constant even if harvest residues are removed. If the land use were to change after harvesting, substantial carbon emissions from belowground biomass and soil could occur (see for instance Searchinger, 2010). However, no land-use change was included in this study and all scenarios and counterfactuals contained either regrowth or continued growth of forest, as the majority of forestland is expected to stay forested (a maximum loss of 13% of total forest area was predicted for 2060, Wear & Greis, 2013).

Secondly, carbon in other non-soil, non-living-tree-biomass (understory, dead wood) was assumed to be a constant carbon stock. This carbon pool is fairly constant from harvest cycle to harvest cycle (Smith et al., 2006). Harvesting even leads to increased carbon storage in this pool, but this assumes harvest residues being left in the forest (Smith et al., 2006). Apart from being a fairly constant carbon pool, it is also relatively small one (several percent of the carbon stored on average in either belowground or tree biomass; Smith et al., 2006). So even if this pool were to change significantly, the effect on the total carbon balance would be very modest.

Thirdly, harvesting always leads to harvest residues. If harvesting residues are used as wood pellet feedstock, their carbon debt was allocated to the harvest residue feedstock and their carbon content was accounted for. If harvest residues are not used as wood pellet feedstock, there are a number of alternatives that were defined as part of the counterfactual scenarios for harvest residues as a feedstock (see section 2.5). It could be argued that the carbon effect of these alternatives should be part of the carbon balance of low-quality roundwood, since it was the roundwood harvesting that caused harvest residue to be formed in the first place. However, it was decided here to only account for harvest residues that are not used for wood pellet production once: via the counterfactuals of harvest residues as a feedstock. The extracted carbon in harvest residues was not directly considered part of the carbon debt of roundwood. Other ways of accounting are conceivable, in which harvest residues are accounted for both on their own and as part of the analysis of roundwood. These alternatives were not considered in full here, as they would likely have a limited impact[43] on the final carbon balance of low-quality roundwood-based pellets used for bioelectricity. However, to still cover the entire potential increase in carbon debt under these alternative accounting systems, the maximum value for the FPE parameter (amount of feedstock required per amount of pellets) was set at 18%, reflecting the potential increased amount of forest biomass (roundwood + harvesting residues) that needs to be extracted to obtain the required amount of feedstock (roundwood)[44].

---

[42] Soil carbon was modelled in other studies on the carbon balance of wood pellets, but this did not result in strong conclusions on how it affected the carbon balance after land use change LUC or harvesting (Zanchi et al., 2010; McKechnie et al., 2011; Mitchel et al., 2012).

[43] In an alternative accounting system, the carbon balance of wood pellets from low-quality roundwood would be negatively impacted if harvest residues are burnt (with or without energy generation) or are left to decompose, as additional emissions are released. The impact is limited though, as harvest residues only form about 15% of total carbon extracted (as assumed by Jonker et al., 2013). Furthermore, harvest residues decompose slowly (see section 2.6) and if harvest residues are used as fuel for other applications (see for example section 2.6), the negative impact would be limited by avoided emissions through replaced fossil fuels. Lastly, in alternative accounting systems, harvest residues, in general may also be allocated to higher value forest products obtained in harvesting (e.g. saw logs).

[44] Based on 15% harvesting residues assumed by Jonker et al., 2013, the potential increase in carbon debt would be 1/0.85. This was included here via a maximum parameter value of FPE that was 1/0.85-1 = 0.176 -> 18% higher than the default value.

2.3 Calculation of carbon sequestration through forest regrowth

After harvesting forests regrow and in the process (re-)sequester carbon. Regrowth was approached here as the regeneration of biomass that was removed during harvest. It was assumed that forests are periodically harvested and that in each harvesting cycle (or: rotation period) consists of a forest is harvested and then regrows to its pre-harvesting biomass level (this is often implicitly assumed in previous studies; see for instance Jonker et al., 2013). The annual amount of biomass regeneration (the regrowth) was determined using a Richards growth function (see formula 8) and rotation periods were based on previous literature (see next subsection and annex I). Biomass regeneration was converted to carbon sequestration values according to formula 7:

$$CS_i = RF_i \cdot CD \tag{7}$$

Where:

CS_i = cumulative carbon sequestration in year i (tonne carbon/MWh)

RF_i = cumulative regenerated fraction in year i (dimensionless)

CD = harvest-associated carbon debt (in tonne carbon · MWh $^{-1}$)

i = year of rotation period

This principle (using formula 7) was applied to all feedstock categories and tree types (softwood / hardwood). The regenerated fraction (**RF**) was based on the biomass regeneration rate (see next subsection). The biomass regeneration rate was assumed to be the same for all four feedstock categories, since they all originate from the same forests[45]. The regeneration rate was varied for softwoods and hardwoods, as softwoods tend to grow faster (e.g. Comas & Eissenstat, 2004). In contrast to regeneration rates, carbon sequestration (**CS**) did differ among feedstock categories, through the harvest-associated carbon debt (**CD**; see formula 7): when considering a larger amount of extracted (carbon in) biomass, the absolute amount of regenerated biomass over time is also larger[46]. Carbon debt values of the different feedstocks (see section 2.2) were used, as further explained in sections 2.7 and 2.8. It was assumed that the amount of carbon stored in belowground and other non-tree natural carbon pools stays constant (as substantiated in section 2.2). Furthermore, no carbon sequestration through forest regrowth was determined for thinnings or when considering the second temporal perspective (as explained in the research overview subsection at the beginning of this chapter); this also holds for regrowth in counterfactual scenarios (see section 2.6).

Forest regrowth: biomass regeneration approached by a Richards function

The Richards growth function (formula 8 with solution formula 9) is an extended version of the logistic differential equation that yields a sigmoid growth curve (see figures 5 and 6) and offers the possibility to vary the so-called point of inflection - essentially the possibility to vary the exact shape of sigmoid curve (Richards, 1959; for a detailed description see also Tsoularis, 2001). This growth function was used because of this flexible shape and because It was developed for (empirical) plant data specifically (Richards, 1959). The Richards growth function forms an option in the GORCAM carbon accounting model and has been used before in carbon balance studies on afforestation (Deckmyn et al., 2004;

---

[45] It may seem counterintuitive to say that mill residues "regrow". However the forests, from which the wood that resulted in the mill residues originates, do regrow. Mill residues may form a small fraction of a harvested amount of wood, but ultimately it takes many trees to yield one tonne of mill residues. The amount of biomass that ended up in mill residues regrows just the same as the biomass that happened to end up in roundwood (see also methodological approach subsection in the beginning of this chapter).

[46] Put differently: each carbon atom extracted is replaced equally fast, but when looking at more atoms extracted, the absolute replaced amount of carbon atoms is higher.

García-Quijano et al., 2008) and on wood pellet biolelectricity studies in the US South-East (Jonker et al., 2013). The Richards growth function is defined as the following differential equation (Richards, 1959; Tsoularis, 2001):

$$\frac{dB}{dt} = r\,B\,\left[1 - \left(\frac{B}{K}\right)^{\beta}\right] \qquad (8)$$

With solution:

$$B(t) = K\,\left[1 - e^{-\beta r(t-t_0)}\left[1 - \left(\frac{B_0}{K}\right)^{-\beta}\right]\right]^{-\frac{1}{\beta}} \qquad (9)$$

With variables:

B = biomass (commonly: in tonne; here: % regenerated)

t = time (year)

And parameters:

r = growth rate (year^{-1})

K = maximum biomass[47] (commonly: in tonne; here: % regenerated)

β = inflection parameter: determines the exact sigmoid shape of the curve (dimensionless)

B_0 = biomass at t = t_0 [48](commonly: in tonne; here: % regenerated)

t_0 = time at B = B_0 (year)

Richards function parameterisations for forest (re)growth are hard to find in literature[49]. The four parameterisations of this study (see table 2) were determined in the following way: First, the rotation period was fixed (see table 2; e.g. a default value of 25 years for softwood); rotation periods were based on previous studies on the carbon balance of wood pellets, with an emphasis on studies that looked at the US South-East specifically (see Annex I for an overview of studies and their rotation period). Secondly, the r, B_0 and β parameters were adjusted to achieve the following: a) the biomass regeneration was exactly 100% at the end of the rotation period (e.g. at 25 years); b) the average annual biomass regeneration was highest at this moment of harvesting (see figure 5; this means that the forest is harvested at the best possible moment in terms of biomass growth efficiency); and c) the

---

[47] In ecology also referred to as *carrying capacity.*

[48] B_0 often refers to the initial biomass in year zero (the null point), strictly however it refers to the amount of biomass at t_0. Values for the parameter pair of B_0 and t_0 fix one specific solution of the differential equation. Here t_0 was not set at zero, enabling a better simulation of the growth pattern of trees, the B_0 parameter therefore is also a positive value, rather than zero. At t = 0 however, the regenerated biomass (B) is near zero, the small positive value for B here is an artefact of this type of function, as using a biomass of exactly zero in the null point, would not yield no growth at all. Here: the nullpoint value of B was adjusted to zero.

[49] Some studies used a Richards function within the GORCAM model (Deckmyn et al., 2004; García-Quijano et al., 2008; Jonker et al., 2013), and even though the GORCAM parameterisation is listed in these studies, the exact parameterisation (specifically the beta parameter) for Richards function itself (i.e. not the GORCAM input parameter "n") is not listed in these studies, nor are the Richards function in the original papers describing the model (Schlamadinger & Marland, 1996b; Schlamadinger et al., 1997), which therefore seems a later, undocumented addition. Other Richards function parameterisations for forests or trees were not found, despite extensive seaching.

sigmoid shape of the regeneration curve (see figure 5) resembles that of forest growth[50] (qualitatively based on Jonker et al., 2013). Thirdly, the t_0 parameter was in all cases set at a value of 5 to further improve the shape of the curve (a value of zero was not desirable, see footnote 48). Lastly, the K parameter (maximum biomass) was always set at 150%, meaning that if a production forest is left unharvested it will ultimately grow towards 150% of its regular, pre-harvesting biomass level (again based on Jonker et al., 2013).

The regenerated fraction (**$\mathbf{RF_i}$**) values of the different years were obtained by taking the B values at each year (i) after harvesting.

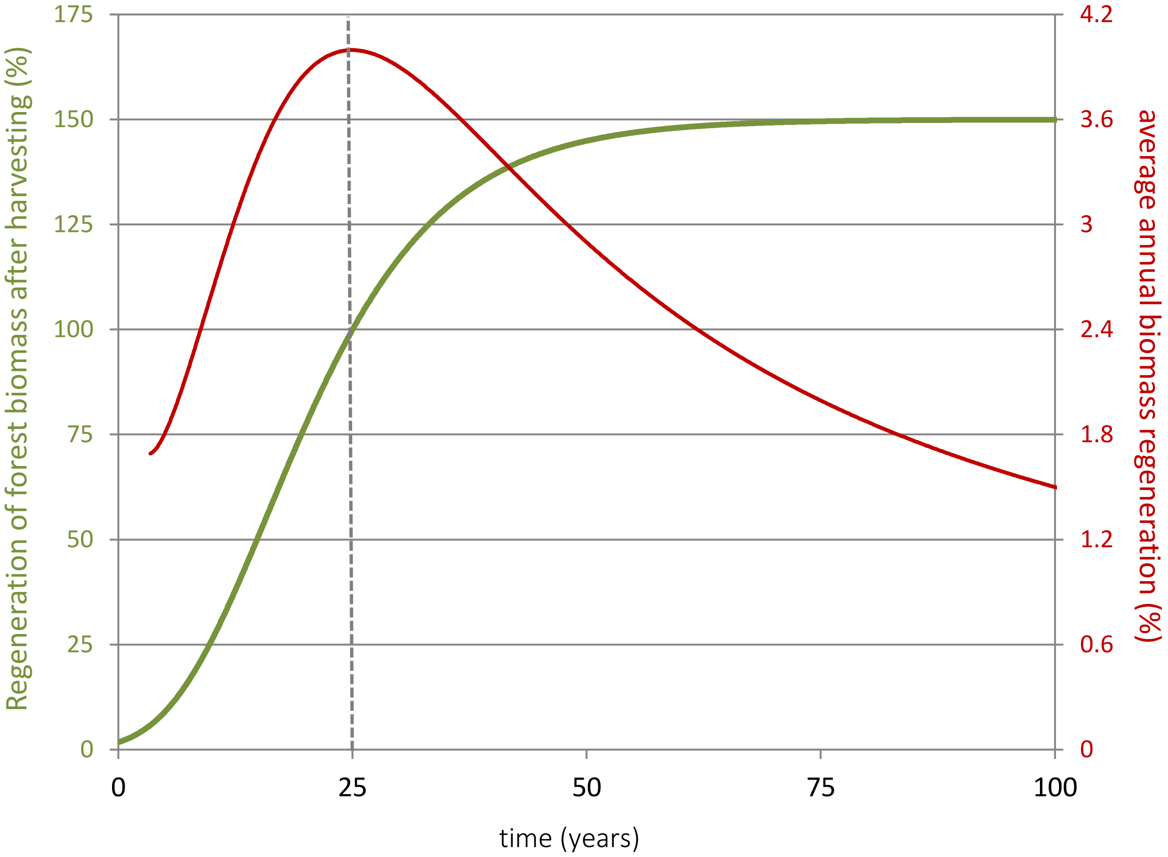


Figure 5. *The regeneration curve of forest biomass was determined based on a fixed rotation period (in this example: 25 years). Parameterisation was such that after 25 years at the moment of harvesting the biomass regeneration was 100% and average annual biomass regeneration was at its highest. Note that average annual biomass regeneration is measured on a separate y-axis (to the right of the graph).*

In this study four different parameterisations were made (see table 2), representing the default, minimum and maximum regeneration rates of softwoods and hardwoods (soft- and hardwood rates partially overlap, see figure 6). These four parameterisations assumed rotation periods of 20, 25, 35 and 50 years (based on annex I) and were constructed as described above, yielding the four regeneration curves depicted in figure 6. These parameterisations reflected differences in growth rate (and therefore rotation period[51]) that could in reality be caused by a number of variables, including intrinsic tree species-specifc traits, environmental conditions and forest management (see introduction).

---

[50] I.e. forest growth rather than for instance bacterial growth, which has an initial growth that is more strongly exponential and flattens out more drastically.

[51] Assuming a rational harvesting regime that maximises biomass output.

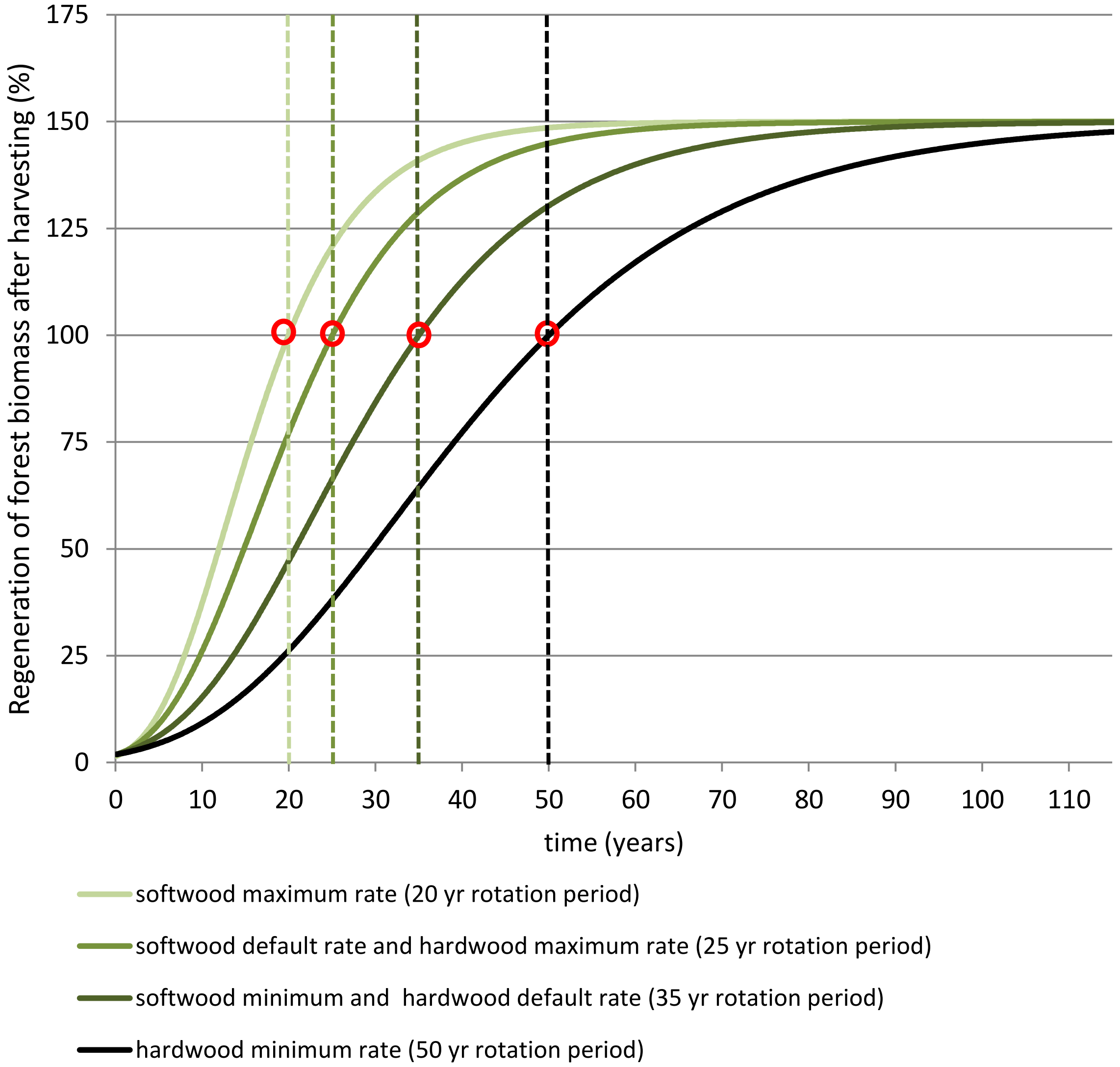


Figure 6. *Default, minimum and maximum regeneration rates for softwood and hardwood forests. Red circles indicate 100% biomass regeneration at the time of harvesting.*

Table 2. *Default, minimum and maximum regeneration rate parameterisation for softwood and hardwood wood pellet feedstocks.*

	parameter	**r**	**K**	**β**	**B_0**	**t_0**
Regeneration rate (rotation period)	*Unit*	*year* $^{-1}$	*%*	*-*	*%*	*year*
hardwood minimum (50 yr)		0.951	150	0.05232	4.500	5
softwood minimum; hardwood default (35 yr)		1.360	150	0.05225	6.250	5
softwood default; hardwood maximum (25 yr)		2.604	150	0.03800	9.046	5
softwood maximum (20 yr)		5.194	150	0.02405	11.600	5

2.4 Calculation of net avoided fossil carbon emissions

Another part of the carbon balance of wood pellets in this study was formed by the net effect of fossil emissions that are *avoided* through the use of wood pellets for bioelectricity on one hand, and the emissions of the wood pellet value chain on the other. Both amounts and their net effect were calculated in tonne carbon [emitted or avoided] per MWh electricity produced from wood pellets. These calculations were independent of feedstock and tree type, except that only the roundwood and thinning feedstock types yield bark, which in turn causes avoided fossil emissions when burned to generate heat.

Avoided fossil carbon emissions

When wood pellets are used to produce electricity, they replace other fuels. In the value chain considered in this study, wood pellets replace coal, as they are co-fired in a coal-fired power plant. Less coal is therefore burned at the power plant, meaning that less fossil carbon is emitted. The (fossil) carbon emissions that are no longer produced are called *avoided emissions*; they were calculated according to formula 10 and the parameters described below:

$$AEC = \frac{1}{\eta} \cdot EFC \cdot 3.6 \tag{10}$$

Where:

AEC = avoided emissions through wood pellets replacing hard coal (tonne carbon / MWh)

η = the efficiency combusting coal for electricity production (dimensionless)

EFC = the emission factor of coal (in tonne carbon / GJ_{LHV}[52])

3.6 = the conversion of GJ to MWh (in GJ/MWh)

The default value for efficiency of combusting coal for electricity (**η**) of 41% was obtained from Sikkema et al. (2010) who based their value on the Amercentrale power plant (part of this study's value chain, see methodological approach section). Minimum and maximum efficiencies were set at 39% and 46% based on the range of efficiencies for Dutch coal-fired power plants in general (ECN, 2007; see table 3). Note that a lower efficiency results in higher avoided emissions. Emission factors of coal (**EFC**) depend on the exact type of coal combusted and the combustion. Blok (2007) provides a general value for bituminous coal of 95 kg CO_2 / GJ_{LHV}. The ETS (European Emissions Trading Scheme) ascribes an emission factor of 98.3 kg CO_2 / GJ_{LHV} to hard coal (RVO, 2015). American coal-fired plants have an average emission factor of 100 kg CO_2 / GH_{LHV} (EPA, 2014). Since the emissions here are *avoided* emissions, the official standard accounting (in the form the ETS) was used for the default emission factor, which was therefore set at 0.0267 tonne C / GJ_{LHV} (based on the 98.3 kg CO_2 value, RVO, 2015; see table 3). The minimum and maximum values were set at 0.259 (based on the general, and more optimistic value of 95 kg CO_2 / GJ_{LHV} in Blok, 2007) and 0.273 (based on the American value of 100 kg CO_2/ GJ_{LHV}), respectively (see table 3). It is important to note that avoided emissions are expressed per MWh electricity produced, referring to amount of electricity that is now produced using wood pellets instead of coal.

The residual bark from the roundwood feedstock category described in section 2.2, as well as residual bark from the thinning feedstock category (which was assumed to yield the same relative amount of residual bark) could be used in various ways (e.g. used as mulch or burned to provide heat) or could simply be burned as waste or left decompose (based on the survey described in 2.1). Here, it was

---

[52] GJ_{LHV} = Gigajoule lower heating value, here it refers to an amount of energy that is harboured in coal and released as heat during combustion. Lower heating value (LHV) means that energy consumed by the evaporation of water that is created in the combustion process is accounted for.

assumed that bark was either burned as waste or used as fuel for drying processes in paper or pellet mills (based on the same survey). When bark is used in this way it reduces fossil fuel use and fossil carbon emissions (based on EEA, 2005) and hence leads to avoided emissions. When bark is used as waste, it simply leads to zero avoided emissions. However, since the carbon in bark is biogenic and already accounted for via the carbon debt, it does not lead to additional emissions in the carbon balance. Avoided emissions were calculated using the following parameters and formula 11:

$$AEF = RB \cdot HCB \cdot EFF \tag{11}$$

Where:

AEF = avoided emissions through residual bark replacing fossil fuels (tonne carbon / MWh[53])

RB = the residual amount of bark per amount of electricity produced from wood pellets (tonne bark / MWh)

HCB = heat content of bark (GJ_{LHV} / tonne bark)

EFF = emission factor of the fossil fuel replaced (tonne carbon / GJ_{LHV})

The minimum values for these parameters were not considered, as the minimum avoided emissions were zero. Residual amount of bark (**RB**) depended on the calculations described in section 2.2 (calculated as 1/ [PEC · TL · FPE] · [DB-1], see section 2.2 for parameters); the default value was 0.166 tonne bark per MWh produced with wood pellets (table 3). The maximum residual amount of bark based on this calculation would be 0.266 tonne / MWh (based on maximum values of PEC, TL, FPE and DB). However, to analyse avoided emissions independent of the size of the carbon debt, a simpler 20% larger maximum value was assumed, yielding 0.199 tonne / MWh. The heat content of bark (**HCB**) was obtained from the ECN (2015) database. The average and maximum dry and ash free (daf) calorific content (heat content) of bark were converted to as received heat contents, resulting in the default parameter value of 14.1 GJ_{LHV} / tonne bark, and maximum value of 17.0 GJ_{LHV} / tonne bark, respectively (table 3). The emissions factor (EFF) depends on the fossil fuel replaced. As described above, it was assumed that bark is used to fuel heating processes in pellet or paper mills. Moreover it was assumed that bark always replaces fossil fuel. The fossil fuel mix used in paper mills is 1/2 natural gas, 3/8 coal, 1/8 oil (EEA, 2005). Based on the emission factors for American stationary sources reported by the EPA (2014), emission factors for fossil fuels (**EFF**) of 0.0153, 0.0273 and 0.0215 tonne C / GJ_{LHV} (for natural gas, industrial coal and crude oil[54] respectively) were used. The default emission factor of 0.0205 tonne C / GJ_{LHV} was based on the aforementioned EEA (2005) ratio, the maximum value of 0.0273 tonne C / GJ_{LHV} was based on coal only (see table 3).

Table 3. *Default, maximum and minimum parameter values for avoided carbon emissions calculations (values for EFC, RB, HCB and EFF were rounded).*

Parameter	**η**	**EFC**	**RB**	**HCB**	**EFF**
Unit	*dimensionless*	*tC / GJ_{LHV}*	*tbark/MWh*	*GJ_{LHV}/tbark*	*tC/GJ_{LHV}*
Default value	0.41	0.267	0.166	14.1	0.0205
Minimum value	0.39[a]	0.259	-	-	0[b]
Maximum value	0.46[a]	0.273	0.199	17.0	0.0273

Unit abbreviations: tC: tonne carbon; tbark: tonne bark. a) Lower efficiency actually results in more avoided emissions. b) No fossil fuels were replaced, as bark was burnt without using the released heat.

---

[53] MWh of electricity generated using wood pellets (pellet procution in turn led to residual bark).

[54] Though crude oil is unlikely to be used at a paper or pellet mill, it does have an emission factor that is representative of various heavier oils that could be used.

It is important to note that burning wood pellets or bark of course does produce (biogenic) carbon emissions that are emitted to the atmosphere. However, these emissions were already accounted for: either via the harvest-associated carbon debt[55], or –when the second temporal perspective was assumed[56] – through forest growth before harvesting. In fact, *all* biogenic carbon extracted from the environment that is released into the atmosphere was accounted for in one of these ways (depending on the temporal perspective) in this study. Besides wood pellets and bark, any biomass that is lost during processing or transport (which was assumed to decompose within the first year), was therefore already accounted for and does not form additional emissions on the carbon balance. Lastly, as explained in the methodological approach subsection (page 12), land-use change emissions (direct or indirect) were not part of this study.

Emissions of the wood pellet value chain

The value chain assumed in this study was based on previous literature (predominantly Dwivedi et al., 2011; Jonker et al., 2013; as well as: Sikkema et al., 2010; Dwivedi et al., 2014; and to a lesser extent: Cherubini et al., 2009; Magelli et al., 2009). First, wood pellet feedstock is grown (including forest management), harvested and transported (by truck) to a pellet mill, where wood pellets are produced, and these pellets are transported (by truck or train) to the nearest main seaport (these steps take place in the US South-East; seaports are listed in footnote 58). The wood pellets are then shipped over the Atlantic to Rotterdam, and transported (by truck or barge) to the Dutch coal-fired power plant at Geertruidenberg (in Dutch: de Amercentrale), where they are co-fired, replacing hard coal. The wood pellet value chain was analysed in its entirety, meaning that literature emission values for the entire chain were used (see table 4), as is further explained in the next paragraph. The value chain emissions only concern fossil fuel emissions and land-use emissions[57] of the wood pellet value chain. In this study all feedstock and wood pellet processing and transport was assumed to be fossil fuel-driven. Emissions from biogenic carbon (e.g. through the burning of wood pellets, bark or through feedstock or pellet losses) were already accounted for via carbon debt (see previous paragraph). As explained in the *Carbon balance and greenhouse gas balance* section of this chapter, greenhouse gas (GHG) emissions were determined in this step (rather than CO_2 emissions only).

The values that were used in this step are listed in table 4, they require some additional explanation. In terms of GHG emissions wood pellet production and transatlantic transport (ocean shipping) are the most important steps, followed by biomass growth and harvest (Magelli et al., 2009; Dwivedi et al., 2011, 2014). Pellet production is in some studies partially fuelled by biomass (e.g. for drying processes; for an overview see table 4), which is then usually viewed as “carbon neutral”. As this study considered the biogenic carbon in biomass separately, emission values were predominantly based on scenarios with fossil fuel fired wood pellet production. Because ocean shipping emissions form a large part of the value chain emissions (e.g. Magelli et al., 2009; Dwivedi et al., 2011, 2014), they were adjusted[58] if shipping distances of the original studies diverged from the distance considered in this study (i.e. when the original study looked at an oceanic transport route other than from the US South-East to the Netherlands). Forest growth and associated forest management GHG

---

[55] The harvest-related carbon debt is the carbon extracted from the environment during harvest and assumed to be fully released to the atmosphere within the first year after harvesting (see section 2.2)

[56] The second temporal perspective assumes the reference amount of carbon stored in the system is determined when trees start growth (see box 2).

[57] e.g. N_2O from fertilisers; note: *not* land-use *change* emissions – which were not part of this study, see introduction

[58] The shipping distance from the US South-East to the Netherlands was 7304 km, based on the average of the shipping distances between Rotterdam (The Netherlands) and the five main wood pellet exporting ports in the US South-East: Savannah, Charleston, Jacksonville, Chesapeake (Norfolk) and Mobile (ports from: T. Young, personal communication, April 10, 2015; shipping distances from: Searates.com, 2015). The shipping emissions in the original studies were multiplied by 7304 km and then divided by the original shipping distance in km (either given in the study or obtained from Searates.com, 2015).

emissions were not included in all studies (see table 4), this was factored in when determining GHG emission values for this study. Inland transport of feedstock and pellets on both sides of the Atlantic forms a small part of the value chain emissions (Magelli et al., 2009; Dwivedi et al., 2011, 2014). Therefore distance adjustments were not made here, and the various modes of transport (truck, train, and barge) in different studies were not specifically investigated. The carbon emission values reported in table 4 were based on reported CO_2-equivalent (CO_2-eq.) values (i.e. they include CH_4 and N_2O alongside CO_2). The CO_2-eq. values were multiplied by 12/44 (i.e. the weight fraction of carbon in the carbon dioxide molecule) to yield carbon values.

Table 4. *GHG emissions of wood pellet value chains in previous literature, shipping distances were adjusted (see note a and e).*

study	**adjusted[a] value chain emissions** (tC / MWh)[b]	**remarks**
Magelli et al. (2009)	0.043 – 0.070	Excludes forest management. Emission values were corrected for shipping distance[e]. Range based on: biomass versus natural gas used for drying step in pellet production. Relatively high CH_4 emissions during natural gas based drying.
Cherubini et al. (2009)	0.029	This study does not accurately define what is included in the value chain. The highest reported value for wood pellet-based electricity was used here.
Sikkema et al. (2010)	0.020 – 0.042[c]	Excludes forest management. Emission values were corrected for shipping distance[e]. Range based on: biomass (only) versus natural gas used for drying step in pellet production.
Dwivedi et al. (2011)	0.081	Full value chain considered (incl. forest management). Some biomass is used for initial drying of feedstock, but the majority of pellet production step is fossil fuel-fired. No shipping distance correction required.
Jonker et al. (2013)	0.048 – 0.057[d]	Full value chain considered (incl. forest management). Some biomass (bark and shavings) is used for feedstock drying. Range based on: different forest management intensity scenarios (low to high intensity). No shipping distance correction required.
Dwivedi et al. (2014)	0.049 – 0.055	Full value chain considered (incl. forest management). Some biomass is used for initial drying of feedstock, but the majority of pellet production step is fossil fuel-fired. Emission values were corrected for shipping distance[e]. Range based on: different forest management intensity scenarios (forming 10-20% of value chain emissions).

Unit abbreviation: tC: tonne carbon. a) Carbon emissions were adjusted for shipping distances where necessary (see remarks for each study). The reason that shipping distance was corrected in this way, instead of for instance comparing tonne-kilometre emission among the different studies, is that the values listed in this table represent the entire value chain at once. b) Carbon emission values were based on reported CO_2-eq. values (i.e. they include CH_4 and N_2O alongside CO_2; CO_2-eq. values were multiplied by 12/44 to yield carbon values). c) The present study's default pellet to electricity conversion efficiency (PEC) value of 0.51 dry tonne pellets/MWh (see section 2.2) was used to convert *per tonne* values to *per MWh* values here. d) The pellet to conversion efficiency of 0.499 dry tonne pellets per MWh reported by Jonker et al. (2013) was used to convert *per tonne* values to *per MWh* values here. e) see text on ocean shipping distance adjustments (bottom page 29).

A default value of ***0.057*** tonne carbon / MWh (electricity produced from wood pellets) was assumed for the wood pellet value chain emissions (**VCE**). This value was based on the emission ranges presented in table 4, the considerations described above and a value chain that included forest management (of average intensity) and fossil fuel-driven pellet production. Based on Dwivedi et al. (2011) a maximum value of ***0.081*** tonne carbon / MWh was assumed. The minimum value was set at ***0.042*** based on fossil fuel-fired scenario by Sikkema et al. (2010).

Net avoided fossil carbon emissions

The net avoided fossil carbon emissions (**NAE**) were calculated from the avoided fossil carbon emissions (caused by wood pellets replacing coal **AEC** and by bark replacing fossil fuels **AEF**[59]) and the value chain emissions of wood pellets (**VCE**), according to formula 12.

$$NAE = AEC + AEF - VCE \qquad (12)$$

Where:

NAE *= net avoided fossil carbon emissions (tonne carbon / MWh)*

AEC *= avoided fossil carbon emissions from wood pellets replacing coal (tonne carbon / MWh)*

AEF *= avoided fossil carbon emissions from bark replacing (a combination of) fossil fuels (tonne carbon MWh)*

VCE *= carbon emissions of the wood pellet value chain (tonne carbon / MWh)*

Avoided fossil emissions were expected to be larger than value chain emissions, resulting in net avoidance (based on Sikkema et al., 2010; Dwivedi et al., 2011, 2014) and a positive effect on the carbon balance. Because the net effect would be avoided (fossil) emissions, the net effect is referred to as the amount of net avoided fossil carbon emissions, despite the fact that value chain emissions were not all CO_2 and not all fossil. Maximum values of net avoided emissions were obtained by taking maximum avoided emissions and minimum value chain emissions, and vice versa to obtain minimum values of net avoided emissions. As a final note, it was assumed that this net effect occurred in year zero (i.e. all avoided and value chain emissions were assumed to happen in less than half a year after harvesting[60]).

---

[59] Only applies to the low-quality roundwood feedstock category.

[60] For forest management emissions (e.g. N_2O from fertilisers) this is quite a rough assumption, but these emissions only form one part of the value chain emissions and in the end they are accounted for.

2.5 Definition of counterfactual scenarios

A counterfactual scenario (or simply: counterfactual) is an alternative scenario, in which a feedstock is not used for wood pellet production (see introduction), here it describes what would have happened to feedstock and the land the feedstock was produced on. The counterfactuals in this study were defined on the basis of previous literature and particularly on a survey held among various forest and wood pellet stakeholders and experts (see annex III, second survey question). In this survey it was asked what would have happened to different feedstock types had there not been a wood pellet demand, i.e. had they not been used for wood pellet production.

Key result of this survey question was that defining counterfactuals is complicated, because of the complex market dynamics and regional differences within the southern forest products market as a whole, and particularly so with respect to the recently strongly expanding wood pellet market. From the survey it also became clear that a large range of possible counterfactuals exist for each feedstock type and multiple counterfactual scenarios may be accurate for one feedstock type at the same time (e.g. a fraction would have never been harvested, another part would have been burned, a third part would have been used for different forest products, etc.). Because of these reasons, and because of their hypothetical nature, it is impossible to draft or verify the perfect (combination of) counterfactual scenario(s). But the counterfactuals in this study, based on the experiences of local experts and stakeholders and previous literature, do present the opportunity to better compare the carbon balance of different feedstocks.

In this study two or three counterfactuals were defined per feedstock type. Counterfactuals defined here are (qualitatively) the same for both hard- and softwoods, as literature and the survey held did not indicate that the general counterfactuals are different for the two wood types (i.e. within the level detail of this study). As land-use change was not part of this study (see introduction) forest regrowth was assumed for all harvesting counterfactuals. However, whether regrowth was included in the calculations of the carbon balance of counterfactuals or not depended on the temporal perspective assumed, as explained in section 2.6. Counterfactuals never included a (harvest-associated) carbon debt, as the counterfactual itself already accounted for (extracted) biogenic carbon.

Counterfactual scenarios for wood pellet production from low-quality roundwood

The survey (see annex III) and previous literature show that many different products are made from low-quality roundwood (Smith et al., 2006), and hence that there are many alternative uses for this feedstock, including the production of (non-exhaustive): paper, oriented strand board (OSB), a range of non-structural panels, and even adult diapers. The first counterfactual for pellet production from low-quality roundwood therefore was defined as:

- ***Counterfactual 1a****:* Low-quality roundwood is used to produce (non-wood pellet) forest products[61], which eventually decay, are burnt, or are landfilled; the harvested forest is replanted and regrows.

The survey also showed that low-quality roundwood is not always utilised. There may be several reasons. Often high-value sawlogs (highest quality roundwood used for timber) are obtained from same forests as low-quality roundwood. The forest is harvested to sell sawlogs, but low-quality roundwood is also harvested (even just to clear the land for new use) and is considered a by-product. It is not always possible for corporate foresters or loggers to find a market for low-quality roundwood, for instance because of the absence of paper or pellet mills within economically viable distance, or because nearby mills use softwood, leaving hardwood without a market or vice versa. These market mismatches often arise through or are exaggerated by the fact that trees take long to grow and the

---

[61] The mix of forest products (and the eventual fates of these products) that was found by Smith et al. (2006) was used in this study, it represents the traditional (pre-pellet boom) forest product mix produced in the US South-East specifically (further discussed in section 2.6).

market develops during growth. Secondly, in exceptional cases it may become beneficial to clear the forest and use the land to grow different trees or for other uses, even if the low-quality roundwood cannot be sold. Thirdly, sometimes only the lowest quality roundwood (non-merchantable to traditional industries) would not have a market when no pellet mills are nearby, or would not go to a pellet mill due to transport costs. In all cases, the low-quality roundwood would not be used. From the survey it became clear that the wood would then simply be left on site or bulldozered over to the side to decompose.

- ***Counterfactual 1b**:* Low-quality roundwood decomposes on site; the cleared forest is replanted and regrows.

The same lack of a market for low-quality roundwood may also lead to the decision to leave forests unharvested, this holds specifically for forests without sawlogs. Other, more general, reasons for maintaining forests may be environmental protection (assumed by for instance: Marland & Schlamadinger, 1997; Mitchell et al., 2012 ; Zanchi et al., 2012; Bernier & Paré, 2013; Jonker et al., 2013 ; Lamers et al. 2014b), recreational purposes, or the lack of an urgent reason for (particularly small-) landowners to reap the benefits of their investment (N. Poudyal, April 15, 2015). In all cases the forest is not harvested and continues to grow:

- ***Counterfactual 1c***: Low-quality roundwood is not harvested; forest continues growth.

This continued growth counterfactual scenario has also been used in many previous studies looking at carbon balance of wood pellets, it is often referred to as a “protection” scenario (Marland & Schlamadinger, 1997; Mitchell et al., 2012; Zanchi et al., 2012; Bernier & Paré, 2013; Jonker et al., 2013 ; Lamers et al. 2014b).

It should be noted that low-quality roundwood is a broad feedstock category; some counterfactuals may be more suited for some sub-categories than for others. Counterfactual 1b may for instance be more likely for non-merchantable roundwood (i.e. not merchantable to traditional forest industries) than for (the merchantable) pulpwood. Another example is that without a market to sell to, counterfactual 1b may be more realistic for low-quality roundwood from corporate owners and 1c for small private owners.

Counterfactual scenarios for wood pellet production from thinnings

Commercial thinnings (merchantable to traditional market) are often used for the same products as pulpwood, or are even considered to be pulpwood (based on the aforementioned survey). The first counterfactual for thinnings is therefore the same as that of low-quality roundwood, with the exception that thinnings by definition are harvested in mid-rotation (during growth - not at the final harvest), the forest therefore continues to grow after thinning[62]:

- ***Counterfactual 2a***: Thinnings are used to produce (non-wood pellet) forest products[61], which eventually decay, are burnt, or are landfilled; the remaining forest continues growth and produces the same pre-harvesting carbon stock as without thinning.

Counterfactual 2a is suited for commercial thinnings (merchantable to traditional market) only.

A second possible counterfactual is to thin forests with the sole goal of increasing forest health and further improving the quality and therefore value of saw logs, leaving thinnings to decompose. According to the survey, large corporate foresters often only thin forests if there is a market for the thinnings. However, this counterfactual may still make economic sense through the increase in forest health and saw log quality.

- ***Counterfactual 2b***: Thinnings decompose on site; the remaining forest continues growth and produces the same pre-harvesting carbon stock as without thinning.

---

[62] In fact it grows faster and it is assumed here that this extra growth fully compensates the carbon extracted during thinning, see section 6.2

A third, more intuitive counterfactual scenario for thinning is simply *not* thinning. The most important reason to include this counterfactual is fact that only a part of the US South's forests is currently thinned (V. Dale, personal communication, April 6, 2015). From the aforementioned survey it came forward that when a market for thinnings is lacking (via mechanisms as described for low-quality roundwood), thinning is often postponed and landowners may ultimately even shift to other silvicultural regimes to reduce reliance on thinning.

- ***Counterfactual 2c***: forests are not thinned and forest growth is normal

This counterfactual is suited for both commercial- and pre-commercial thinnings.

Counterfactual scenarios for wood pellet production from harvest residues

A commonly used counterfactual scenario for harvest residues is to leave them on site to decompose (Repo et al., 2010, 2011; McKechnie et al., 2011; Zanchi et al., 2012; Lamers et al., 2013a; Stephenson & MacKay, 2014). The survey held for this study confirmed that in the US South-East many harvest residues are left in the forest, as they have little monetary value.

- ***Counterfactual 3a***: Harvest residues are left in the forest to decompose; after harvesting the forest is replanted and regrows.

Another possible counterfactual is to burn harvest residues (McKechnie et al., 2011; Lamers et al., 2013a; Lamers et al., 2014b; Stephenson & MacKay, 2014), either to prep the land for the next rotation or simply to get rid of them.

- ***Counterfactual 3b***: Harvest residues are burnt (without energy capture); after harvesting the forest is replanted and regrows.

The aforementioned survey showed that harvest residues are sometimes also burnt at (predominantly) paper mills or other mills types, to provide heat for drying processes, replacing fossil fuels (EEA, 2005)

- ***Counterfactual 3c***: Harvest residues are burnt at mills to provide heat, replacing fossil fuels; after harvesting the forest is replanted and regrows.

Continued forest growth (i.e. not harvesting) would increase the amount of carbon in "would be" harvesting residues. However, since the decision to harvest per definition never depends on harvest *residues*, a continued forest growth counterfactual is not considered for this feedstock type.

Counterfactual scenarios for wood pellet production from mill residues

The survey among wood pellet experts and stakeholders indicated that "mill residues are fully allocated in the market since they are a superior substitute to using roundwood in almost all fiber or fuel based applications" - Hazel (2015; essentially capturing the different responses to the survey)[63]. This leaves two main counterfactual scenarios. First, mill residues could be used in similar applications as low-quality roundwood. It was assumed that mill residues are used for the same mix of forest products as low-quality roundwood[61]. Mill residues ultimately orginate from some forest, in the counterfactuals it is assumed that this forest regrows (this is the same as in the factual, i.e. pellet production, see section 2.3).

- ***Counterfactual 4a***: Mill residues are used to produce (non-wood pellet) forest products[61], which eventually decay, are burnt, or are landfilled; after harvesting the forest (from which the mill residues ultimately originated) is replanted and regrows.

This counterfactual is most accurate for "clean" mill residues (without too much bark).

---

[63] Dr Hazel added that this full allocation implies that when mill residues are used for pellets, someone else has to use roundwood. This would probably be best accounted for via the carbon debt, however this "indirect carbon debt" (similar to indirect land-use change) is beyond the scope of this study.

The second counterfactual scenario for mill residues is that they are burnt as a fuel (based on the survey). It was assumed that mill residues, like harvest residues, would be predominantly burnt at paper mills, thereby providing heat for drying processes and replacing fossil fuels (EEA, 2005)

- ***Counterfactual 4b***: Mill residues are burnt at mills to provide heat, replacing fossil fuels; after harvesting the forest (from which the mill residues ultimately originated) is replanted and regrows.

This counterfactual would be suitable for both clean and dirtier (higher bark content) residues.

Like for harvesting residues, continued forest growth (i.e. not harvesting) would increase the amount of carbon in "would be" mill residues. Again, the decision to harvest per definition never depends on mill *residues*. A continued forest growth counterfactual is therefore not considered for this feedstock type.

2.6 Calculation of carbon sequestration or emission in the counterfactual scenarios

The cumulative net carbon emission or sequestration in the counterfactual scenarios (**CC**) over time was calculated using the following two formulas:

$$CC1_i = CD \cdot (RF_i - EF_i) \qquad (13)$$

$$CC2_i = CD \cdot (1 - EF_i) \qquad (14)$$

Where:

$CC1_i$ = cumulative net carbon emission or sequestration in the counterfactual scenario in year i assuming the first temporal perspective (in tonne carbon / MWh[64])

$CC2_i$ = cumulative net carbon emission or sequestration in the counterfactual scenario in year i assuming the second temporal perspective and/or when using thinnings as feedstock (in tonne carbon / MWh[64])

CD = harvest-associated carbon debt of a single harvest (in tonne carbon / MWh)

EF_i = cumulative emitted (or sequestered: negative number) fraction in year i (dimensionless)

RF_i = cumulative regenerated fraction in year i (dimensionless)

i = year after what would be harvesting for wood pellets in the factual scenario

The main aspect of the counterfactual scenarios in this study is what would have happened to the biogenic carbon in the wood pellet feedstock had the feedstock not been used to produce wood pellets. In most counterfactuals carbon is ultimately emitted to the atmosphere, as described by the emitted fraction of a certain year (**EF**$_i$), the remaining fraction is remains stored. If carbon is sequestered rather than emitted, emitted fractions have negative values. All EF$_i$ values were determined per counterfactual and are further described in the next four subsections.

The amount of (biogenic) carbon that undergoes the counterfactual scenario was an amount equal to the (harvest-associated) carbon debt (**CD**; in tonne carbon / MWh) of each feedstock. The reason being that carbon debt exactly represents the amount of biomass and its carbon content that would be required for wood pellet production and ultimately an amount of bioelectricity (in the *factual* scenario), but now undergoes the *counterfactual*. Note that counterfactuals in this study were thus scaled to the harvest-associated carbon debt (see formula 13 and 14) of each feedstock (see section 2.2), but did not *include* a carbon debt (as extracted biogenic carbon would otherwise be accounted for twice). Even when considering the second temporal perspective (taking the reference carbon stock when trees start growing), which does not include a carbon debt in its own analysis, the carbon debt values of the different feedstocks were used to scale the counterfactuals of those feedstocks (see formula 14). For thinnings, for which no carbon debt value was seperately determined, carbon debt values of roundwood was used. The reason being that thinnings are essentially formed by young roundwood, with similar characteristics (bark fraction, carbon content; harvest residures - the relevance of these characteristics for the carbon debt calculation can be found in section 2.2).

Forest regrowth was part of the counterfactual scenario (where applicable[65]), when assuming the first temporal perspective (taking reference carbon stock before harvesting, see box 2), as shown

---

[64] Even if counterfactuals do not produce electricity, amounts of carbon are still scaled per MWh electricity that could be produced from the carbon's corresponding amount of wood pellets.

in formula 13. Regrowth was calculated as described in section 2.3 (i.e. assuming regeneration of biomass), using the regenerated fraction (**RF_i**) of each year after harvesting. When assuming the second temporal perspective (taking the reference carbon stock when trees start growing), forest regrowth was not included in the counterfactual (see formula 14), as carbon sequestration through forest regrowth was attributed to the next harvest. At the same time this resulted in higher carbon stocks in year zero than under the first perspective. This is because the year zero was always set just before harvesting in this study, meaning that (in the second temporal perspective) carbon had already been accumulating in biomass before year zero, as the reference carbon stock was determined at planting. The amount by which the carbon stocks are higher in year zero was the harvest-associated carbon debt (**CD**), explaining the number **1** in formula 14. The reason being that the forest had exactly regenerated up to the amount of carbon in the carbon debt (which represents the biomass and its carbon content that now undergo the counterfactual scenario). The overall carbon emission or sequestration in the counterfactuals of thinnings were always calculated using formula 14, regardless of the temporal perspective. For thinnings the number **1** in formula 14 can be explained as the additional biomass that is generated due to thinning. This is due to the assumption that thinnings never result in lower final harvests (for details see section 2.1).

The following subsections principally describe the calculations of the emitted fraction (EF_i), other components of the counterfactuals (see formulas 13 and 14) were obtained from previous sections.

Counterfactual scenarios for wood pellet production from low-quality roundwood

***Counterfactual 1a**:* Low-quality roundwood is used to produce (non-wood pellet) forest products, which eventually decay, are burnt, or are landfilled; the harvested forest is replanted and regrows.

The emitted fraction (EF_i) of this counterfactual was based on research by Smith et al. (2006), in which the destination of carbon in harvested wood was modeled over time. In this study by Smith et al. (2006) carbon in wood ends up in one of four categories: in use in forest products (paper, oriented strand board (OSB), a range of non-structural panels, etc. see Smith et al., 2006 for details), in landfills, burned for energy, and burned without capturing energy[66]. Fractions specific for the US South-East and for pulpwood were obtained from Smith et al. (2006; table 6) and used in this study; specific distinct datasets were used for soft- and hardwoods. The 'in use as forest products category' as defined by Smith et al. (2006) includes various forest products, providing a good representation of the traditional pulpwood market, as this study was performed in 2005 - before the real pellet boom (Spelter & Toth, 2009)[67].

The emitted fraction was calculated as the sum of the (cumulative) burned for energy fraction and the (cumulative) burned without energy capture fraction. The fractions calculated by Smith et al. (2006) were not calculated every year: beyond ten years, fractions were only calculated in five year intervals, fractions in missing years were determined through linear extrapolation. In this counterfactual no additional emissions were included for the production of the forest products (paper, OSB, etc.), other than the emissions of the "burned for energy" fraction. The fractions of wood burned

---

[65] Forest regrowth was never part of counterfactuals 1c, 2a and 2b, because in these scenarios the forest is not harvested (see below for calculations, section 3.5 for explanations of the scenarios). It may seem counter-intuitive to include forest regrowth in the counterfactual scenario of harvest or mill residues, but as explained in section 2.3, forest regrowth was approach in this study as regeneration of biomass and the biomass that residues consist of also regenerates.

[66] Initially wood is in use as products, burned for energy or burned without energy capture. Over time more wood prodcuts end up being burned or landfilled.

[67] The decomposition pattern of these forests products combined is similar to that of for instance paper on its own, so even if the distribution of pulpwood over different products has changed over the last decade, the carbon storage over time will be similar (decomposition patterns of the mix vs paper alone were made using Smith et al., 2006, tables 6 and 8).

in year zero represented the lowest quality share of roundwood (bark, residues or below pulpwood quality roundwood) which are not suited for traditional forest products manufacture (Smith et al., 2006, p. 200); they were included in the calculations of this counterfactual, because the carbon in this lowest-quality share of roundwood also had to be accounted for.

In the final calculation of the emitted fraction a correction was made for methane released from landfills. Ultimately, 20% of the carbon in landfilled wood is released as methane[68] (Ingerson, 2010, based on EPA 2006). This methane emission was not included in Smith et al. (2006). It was included in this study by taking 20% of the fraction of carbon in landfills after 100 years (which at that time is already stabilised), and assuming that 1/100 of that 20% is released annually as methane. The emitted fraction was then adjusted using a GWP_{100} value of 28 for methane (IPCC, 2013). This was quite a rough approach, as methane is released relatively early and the exact methane emissions are uncertain (Ingerson, 2010). The default cumulative annual emitted fractions ($\mathbf{EF_i}$) were therefore based on the average fractions including and excluding the methane correction. Maximum fractions fully included- and minimum fractions fully excluded the methane correction. As an illustration the resulting emission trajectories (for softwood) are shown in figure 7.

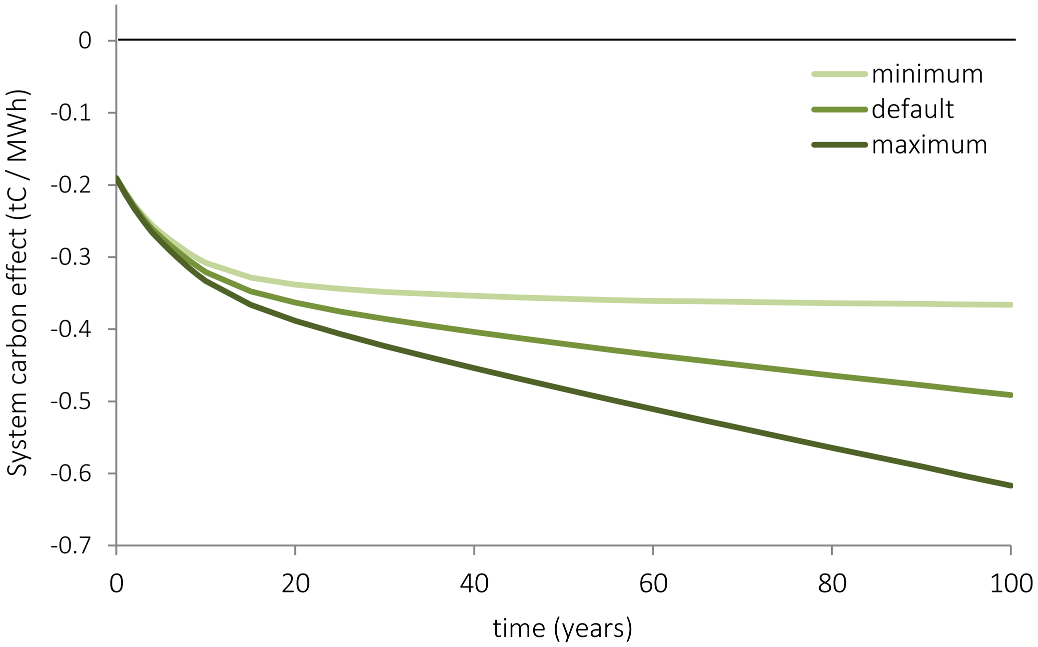


Figure 7. *Greenhouse gas emission trajectories of softwood roundwood in counter-factual 1a. Note that significant emissions take place in year zero.*

Counterfactual 1b: Low-quality roundwood decomposes on site; the harvested forest is replanted and regrows.

Precise understanding of decomposition dynamics is limited (Noormets et al., 2012) and is often approached in a model separate form the carbon balance as a whole (e.g. Guest et al., 2012). Cumulative annual emitted fractions ($\mathbf{EF_i}$) in this study were based on a recent overview of decomposition rates of downed woody debris (DWD) by Russell et al., (2014). Soft- and hardwood were analysed seperately, based on the seperate sets of half-lives presented by Russell et al. (2014). These authors also calculated half-lives per average annual temperature category (higher temperatures lead to shorter half-lives). Relatively slow decomposition was assumed for low-quality roundwood, as it consists of larger pieces of wood than DWD (See table 5). The minimum emitted fractions were based on the longest half-life presented in this study (i.e. at the lowest temperature). Maximum emitted fractions were based on the average half-life over the given temperature range.

---

[68] Based on Ingerson (2010) it was assumed that no other greenhouse gases were released from landfills.

Lastly, default emitted fractions were the average of these minimum and maximum half-lives. Like roundwood, DWD includes bark, therefore no further correction for bark was made here.

Table 5. *Half-lives of roundwood that emitted fractions were based on.*

decomposition rate and therefore emitted fraction	**half-lives of roundwood (year)**	
	softwood	*hardwood*
default	20.4	10.5
minimum	22	11
maximum	18.8	10

Counterfactual 1c: Low-quality roundwood is not harvested; forest continues growth.

This counterfactual was different from the others in two aspects. First, it did not include forest regrowth, as the forest was not harvested, meaning that the regenerated fraction (**RF_i**) through forest regrowth was zero in all years i. Secondly, the cumulative emitted fraction (**EF_i**) of carbon was negative for all years i, as carbon was sequestered rather than emitted through continued forest growth.

The negative values for the emitted fractions – from here on referred to as the *sequestered fraction*, were determined from the regeneration curves described in section 2.3. The increase in biomass levels beyond the ('what would have been') harvesting point (i.e. beyond 100% regenerated biomass, see figure 5) was converted to a cumulative sequestered fraction in year i after this 'harvesting point'. As an example: if in year i = 1 biomass levels are 105%, cumulative the sequestered fraction was set at 0.05, if in year i = 2 biomass levels are 108%, the cumulative sequestered fraction was 0.08, etc. Default, minimum and maximum values for soft- and hardwoods were based on their respective regeneration curves in section 2.3 (maximum growth rate leads to minimum emitted fraction (i.e. the most negative emitted fractions – most carbon sequestered).

Counterfactual scenarios for wood pellet production from thinnings

Counterfactual 2a: Thinnings are used to produce (non-wood pellet) forest products, which eventually decay, are burnt, or are landfilled; the remaining forest continues growth and produces the same pre-harvesting carbon stock as without thinning.

The calculation of the emitted fraction (**EF_i**) was exactly the same as in counterfactual 1a. Based on the survey held (see annex III), it was assumed that thinnings can be used for the same applications as roundwood (see Smith et al., 2006).

Counterfactual 2b: Thinnings decompose on site; the remaining forest continues growth and produces the same pre-harvesting carbon stock as without thinning.

The calculation of the emitted fraction (**EF_i**) was exactly the same as in counterfactual 1b. Thinnings are essentially formed by young roundwood, with similar characteristics (bark fraction, moisture content, carbon content) and were therefore assumed to decompose at the same rate as low-quality roundwood.

Counterfactual 2c: forests are not thinned and forest growth is normal

It was assumed in this study that thinnings never result in lower final harvests, because thinnings are always additionally created biomass (extracted biomass is compensated by increased growth; see the thinning assumption subsection of 2.1). In this counterfactual no thinnings were made, so no additional biomass was created. This was modeled by an emitted fraction (**EF_i**) value of 1 for all years i in formula 14, which cancels out the number 1 that was included to represent the additional biomass in case of thinnings. The carbon effect of the counterfactual (**CC_i**) was therefore zero in all years i.

Counterfactual scenarios for wood pellet production from harvest residues

Counterfactual 3a: Harvest residues are left in the forest to decompose; after harvesting the forest is replanted and regrows.

Calculations of the cumulative emitted fraction (EF_i) over time in this counterfactual were the exact same as in counterfactual 1b. With one exception: since harvest residues are roughly similar in size to downed woody debris (DWD; for which half-lives values were available), the default emitted fraction was based on the overall average half-life reported by Russell et al., (2014), minimum and maximum fractions were based on the longest and shortest half-lives, respectively (see table 6).

Table 6. *Half-lives of harvest residues that emitted fractions were based on.*

decomposition rate and therefore emitted fraction	**half-lives of roundwood (year)**	
	softwood	*hardwood*
default	18.8	10
minimum	22	11
maximum	14	8

Counterfactual 3b: Harvest residues are burnt (without energy capture); after harvesting the forest is replanted and regrows.

Greenhouse gas gas emissions of burning wood and wood products form 101.23% to 101.94% of CO_2 emissions only (WDNR, 2010; EPA, 2014; IPCC, 2013). These percentages were assumed to apply to harvest residues as well. Emissions all occur in year zero. The emitted fraction in year zero (**EF_0**) therefore was **1.0158** (based on the average of the aforementioned 101.23% and 101.94%). The minimum value was the CO_2 only emitted fraction in year zero (EF_0) of **1**. The maximum emitted fraction in year zero (EF_0) was set at **1.0317** (based on the absolute difference between the minimum and default fractions). The cumulative emitted fraction in year i (EF_i) remained constant after year zero.

Counterfactual 3c: Harvest residues are burnt at mills to provide heat, replacing fossil fuels; after harvesting the forest is replanted and regrows.

This counterfactual includes emissions from burning harvest residues and avoided fossil fuel emissions. The emitted fraction in year zero of this counterfactual (**EF_{3c0}**) is the net effect of the emissions and avoided emissions (see formula 15[69]). The emitted fraction values of burning harvest residues were the emitted fraction values of counterfactual 3b (**EF_{3b0}**). The avoided fossil fuel emission fraction (**AF**) from using harvest residues to provide heat was calculated according to formula 16.

$$EF_{3c\,0} = EF_{3b\,0} - AF \qquad (15)$$

$$AF = (HCW\ \cdot EFF)/FCC \qquad (16)$$

---

[69] Note that a maximum value for EF_{3c0} was obtained using a maximum value for EF_{3b0} and a minimum value for AF, et vice versa for minimum values of EF_{3c0}.

Where:

$EF_{3c\,0}$ = Emitted carbon fraction in year zero in counterfactual 3c (dimensionless)

$EF_{3b\,0}$ = Emitted carbon fraction in year zero in counterfacual 3b (dimensionless)

AF = Avoided carbon emission fraction (dimensionless)

HCW = Heat content of wood (GJ_{LHV} / tonne wood[70])

EFF = emission factor of the fossil fuel replaced (tonne carbon / GJ_{LHV})

FCC = carbon content of feedstock (tonne carbon / tonne feedstock)

The heat content of wood (**HCW**) was obtained from the ECN phyllis2 database (2015) and was converted from dry and ashfree (daf) to as received (ar) values (using ash and moisture content values). It was assumed that the heat content of wood is the same as harvest residues. Minimum and maximum values were based on the minimum and maximum daf values for heat content of wood in the ECN (2015) database (see table 7). The fossil fuel mix used in paper mills is 1/2 natural gas, 3/8 coal, 1/8 oil (EEA, 2005). The emission factors of the replaced fossil fuels (**EFF**) were based on American stationary sources reported by the EPA (2014): emission factors of 0.0153, 0.0273 and 0.0215 tonne C / GJ_{LHV} for natural gas, industrial coal and crude oil[71], respectively. The default emission factor was based on the aforementioned EEA (2005) ratio, the maximum value of was based on replacing coal only and minimum value on replacing natural gas only (see table 7). Carbon content (**FCC[72]**) values of wood were obtained from calculations in section 2.2 (see table 7). As harvest residues were assumed to be used locally, no transport emissions were included in the calculation.

Coming back to the resulting cumulative emitted fractions in year i in this counterfactual (EF_{3ci}): they remained constant at the level of the emitted fraction in year zero (EF_{3c0}). All emissions took place or were avoided in year zero; no further emissions were part of this counterfactual.

Table 7. *Default, maximum and minimum values of the emitted fraction in year zero of counterfactual 3c and the parameters required for its calculation. Note that a negative value means sequestration.*

Parameter	**$EF_{3c\,0}$**	**$EF_{3b\,0}$**	**AF**	**HCW**	**EFF**	**FCC**
Unit:	*dimensionless*	*dimensionless*	*dimensionless*	*GJ_{LHV}/twood*	*tC/GJ_{LHV}*	*tC/twood*
softwood						
default value	0.249	1.016	0.767	16.1	0.0205	0.430
minimum value	-0.141	1.000	0.572	13.7	0.0153	0.366
maximum value	0.032	1.032	1.141	21.1	0.0273	0.504
roundwood						
default value	0.254	1.016	0.762	16.0	0.0205	0.430
minimum value	-0.013	1.000	0.539	12.9	0.0153	0.366
maximum value	0.492	1.032	1.013	18.7	0.0273	0.504

Unit abbreviations: tC: tonne carbon; twood: tonne wood.

---

[70] Harvest residues were assumed to have the same heat content as wood

[71] Though crude oil is unlikely to be used at a paper or pellet mill, it does have an emission factor that is representative of various heavier oils that could be used.

[72] For consistency the abbreviation FCC is used: feedstock carbon content; in this case the carbon content of harvest residues.

Counterfactual scenarios for wood pellet production from mill residues

Counterfactual 4a: Mill residues are used to produce (non-wood pellet) forest products, which eventually decay, are burnt, or are landfilled; after harvesting the forest (from which the mill residues ultimately originated) is replanted and regrows.

The calculation of the emitted fraction (EF_i) was exactly the same as in counterfactual 1a, with one exception. The survey held (see annex III), showed that mill residues can be used for the same fiber applications as roundwood (paper, OSB, etc.) and that in fact they even are a superior substitute. This led to the following adjustment: The initial (year zero) burning with or without energy capture categories (in Smith et al., 2006, table 6) were excluded. This was done because the entire amount of mill residues is suitable to manufacture forest products (in contrast to low-quality roundwood and thinnings categories which have parts that are less usable – e.g. below-pulpwood-quality roundwood and bark). Methane emissions were accounted for in the same way as in counterfactuals 1a and 1b, resulting in the minimum, default and maximum emitted fractions (corresponding with the emission trajectories in figure 8, for softwood). These adjustments result in no emissions in year zero ($EF_0 = 0$) , but more emissions later on (see figure 8), this is because relatively more of the carbon in mill residues ends up in landfills, releasing more methane (except for the minimum trajectory for which no methane emissions were included).

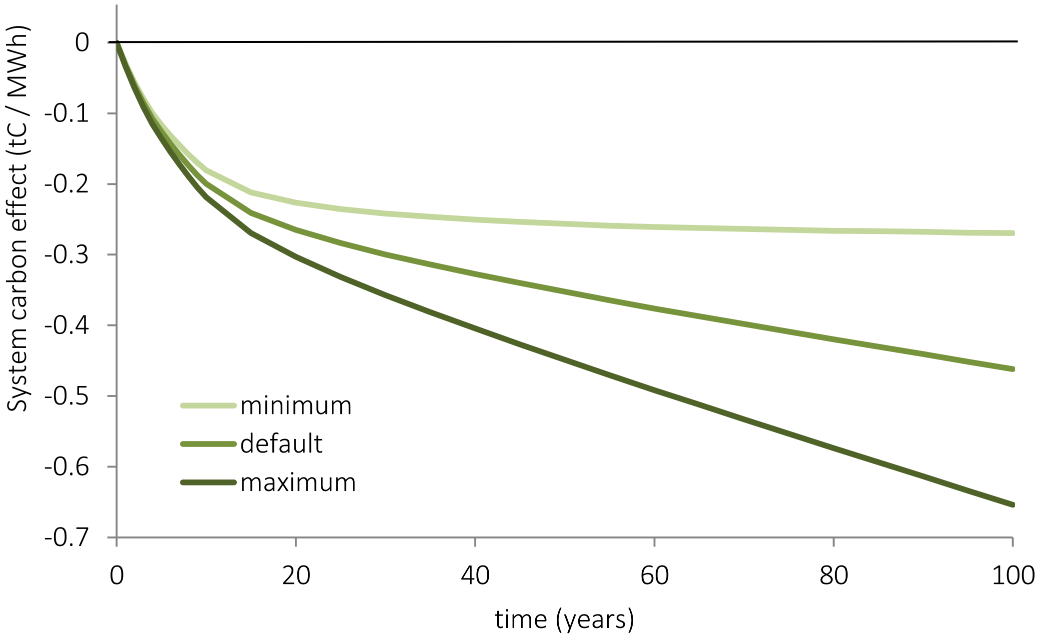


Figure 8. *Greenhouse gas emission trajectories of softwood roundwood in counter-factual 4a. Note that no emissions take place in year zero.*

Counterfactual 4b: Mill residues are burnt at mills to provide heat, replacing fossil fuels; after harvesting the forest (from which the mill residues ultimately originated) is replanted and regrows.

The default, minimum and maximum cumulative emitted fractions in year i (EF_i) were exactly the same as in counterfactual 3c. The carbon content and heat content of mill residues were assumed to be the same as those of wood. The same assumption was made for harvest residues in counterfactual 3c, so the calculations and outcomes for emitted fractions were the same (see formulas 15 and 16, and table 7).

2.7 Calculation of carbon debt payback times

Carbon debt payback times were calculated using formula 1 and condition 2.

$$CB1_i = -CD + NAE + CS_i \tag{1}$$

$$carbon\ debt\ payback\ time\colon\ year\ i\ for\ which\ CB_i = 0 \tag{2}$$

Where:

$CB1_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the first temporal perspective (tonne carbon / MWh)

CD = cumulative[73] harvest-associated carbon debt (tonne carbon / MWh)

NAE = cumulative[74] net avoided fossil carbon emissions (tonne carbon / MWh)

CS_i = cumulative carbon sequestration in year i (tonne carbon / MWh)

i = year after harvesting

The cumulative harvest-associated carbon debt (**CD**), cumulative carbon sequestration through forest regrowth (**CS**$_i$), and cumulative net avoided fossil carbon emissions (**NAE**) were determined in sections 2.2, 2.3 and 2.4 respectively. The carbon balance (**CB$_i$**; see formula 6) is the (cumulative) carbon effect of using wood pellets for bioelectricity in a certain year i after harvesting. The carbon debt payback time is reached when condition 2 holds, i.e. when the carbon debt, corrected for avoided emissions, is repaid through forest regrowth. Since the carbon debt only consisted of the harvest-associated carbon debt (and no LUC-related carbon debt), the carbon debt payback time had to lie between zero and one full rotation period, or would never be reached[75]. Carbon debt payback times were rounded up, for instance a calculated carbon debt payback time of 15.3 years became a carbon debt payback time of 16 years, this was done because 16 in this case marks the first year in which no debt was left.

Carbon payback times were only calculated when considering the first temporal perspective (taking reference carbon stock before harvesting, see box 2). When applying the second temporal perspective (taking reference carbon stock before harvesting, see box 2) or when looking at thinings specifically (regardless of temporal perspective), carbon debt payback times did not require calculations: in these cases no carbon debt was considered, resulting in carbon debt payback times of zero years.

The shortest and longest possible payback times were calculated, by trying all combinations of the minimum and maximum values for each of the different components (carbon debt, net avoided emissions and regeneration rate – via the regenerated fraction RF$_i$[76]). The sensitivity analysis on the carbon debt payback time was done by varying one component at a time from the minimum to the default to the maximum value. Note that the net avoided emissions were not dependent on the carbon debt. The carbon sequestration was scaled using the carbon debt, but the underlying regenerated fraction (RF$_i$; see section 2.3) was also independent of the carbon debt. Both these independencies were crucial to: 1) determine the overall minimum- and maximum carbon debt payback times, because the maximum and minimum values of the three components could be combined to yield the shortest and longest payback times; and 2) perform the sensitivity analysis, because each component could be varied independently.

---

[73] A cumulative carbon debt means that after each harvest a new debt was added to the carbon balance.

[74] Cumulative net avoided emissions mean that after each harvest, the net avoided emissions that arise from the use of the harvested biomass were added to the carbon balance.

[75] This is because at the end of each rotation period a new equally large debt is created by harvesting (in order to produce the same amount of wood pellets), so if the carbon debt is not repaid within one rotation period, it would be repaid.

[76] When regeneration rates were varied, the rotation periods were varied accordingly (see section 2.3)

2.8 Calculation of carbon parity payback times

Carbon parity payback times were calculated using formulas 1 and 3 and conditions 4 and 5.

$$CB1_i = -CD + NAE + CS_i \qquad (1)$$

$$CB2_i = NAE \qquad (3)$$

$$carbon\, parity\, payback\, time\colon\; year\; i\; for\; which\; CB1_i = CC1_i \qquad (4)$$

$$carbon\, parity\, payback\, time\colon\; year\; i\; for\; which\; CB2_i = CC2_i \qquad (5)$$

Where:

$CB1_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the first temporal perspective (tonne carbon / MWh)

$CB2_i$ = carbon balance of using wood pellets for bioelectricity in year i assuming the second temporal perspective and/or when using thinnings as feedstock (tonne carbon / MWh)

CD = cumulative[77] harvest-associated carbon debt (tonne carbon / MWh)

NAE = cumulative[78] net avoided fossil carbon emissions (tonne carbon / MWh)

CS_i = cumulative carbon sequestration in year i (tonne carbon / MWh)

$CC1_i$ = net cumulative carbon emission or sequestration in the counterfactual scenario in year i assuming the first temporal perspective (tonne carbon / MWh)

$CC2_i$ = net cumulative carbon emission or sequestration in the counterfactual scenario in year i assuming the second temporal perspective and/ or when considering thinnings (tonne carbon / MWh)

i = year after (what would be) harvesting for wood pellet production in the factual scenario

The carbon balance (**CB_i**; see formula 1 for the first temporal perspective and 3 for the second) is the (cumulative) carbon effect of using wood pellets for bioelectricity in a certain year i after harvesting. When CB_i equals the (cumulative) carbon effect of the counterfactual (**CC_i**; from the corresponding temporal perspective), carbon parity is reached (conditions 4 and 5): the factual (wood pellet use for bioelectricity) and the counterfactual have the same system carbon effect. Carbon parity payback times where calculated for all feedstock types and temporal perspectives. For thinnings formula 3 and condition 5 were always used, regardless of the temporal perspective assumed (due to the assumption that thinnings never result in lower final harvests, for details see section 2.1). Carbon parity payback time (in years) was always rounded up, marking the first year in which the factual had a more positive system carbon effect than the counterfactual.

The system carbon effects of the factual carbon balance and the counterfactuals were calculated over multiple rotation periods (up to 100 years from the first harvest). The minimum, maximum and default duration of rotation periods for soft- and hardwood were determined in section 2.3. For both factual and counterfactual, any (avoided) carbon emissions and carbon sequestration were tracked over time (e.g. regrowth followed rotation periods, carbon debt was subtracted and net avoided emissions added after each harvest, etc.), meaning that stored carbon could compile over time. Two counterfactuals were different in the sense that they did not include harvesting or rotation

---

[77] A cumulative carbon debt means that after each harvest a new debt was added to the carbon balance.

[78] Cumulative net avoided emissions mean that after each harvest, the net avoided emissions that arise from the use of the harvested biomass were added to the carbon balance.

periods: the continued growth counterfactual (1c; included continued growth over the course of 100 years, see section 2.6) and the no thinning counterfactual (2c; no harvesting of *thinnings,* i.e. a carbon balance of zero, see section 2.6).

As in section 2.7, the shortest and longest possible payback times were calculated, by trying all combinations of the minimum and maximum values for each of the different components. This was done for both the carbon balance of the factual (CB) and the carbon effect of the counterfactual (CC); it is important to note that when calculating a (minimum/default/maximum) carbon parity payback time, the same set of parameter values was used for both CB and CC[79]. What components should be minimal or maximal to reach shortest or longest parity payback times differed among counterfactuals, but they were always analysed using the same parameter set for the factual carbon balance. The sensitivity analysis on the carbon debt payback time was done by varying one component at a time from the minimum to the default to the maximum value. Like the regenerated fraction and the net avoided emissions (as described in section 2.7), the emitted carbon fraction of the counterfactuals was calculated independently from the carbon debt. As explained in section 2.7 these independencies were crucial to determine the overall minimum- and maximum carbon debt payback times and to perform the sensitivity analysis.

---

[79] The reasons this is important is that it would for instance be unfair to compare a factual carbon balance with slow biomass regeneration to a counterfactual with fast biomass regeneration.

3. Results

The results of this study consist of the carbon debt payback times and carbon parity times of using wood pellets from different feedstocks to produce bioelectricity. Default, minimum and maximum payback times are presented. The influence of feedstock type, tree type, temporal perspective and counterfactual type (for carbon parity only) on these payback times is shown. Furthermore, using the results of the sensitivity analysis, the individual effect of each research component (carbon debt, regeneration rate, net avoided emissions and carbon emissions of the counterfactual) is set out.

Carbon debt payback times

Carbon debt payback times and carbon balances of wood pellets used for bioelectricity were similar for all studied feedstock types, except thinnings (figures 9 [thinnings not displayed] and 10). When considering the first temporal perspective (taking reference carbon stocks just before harvesting), an initially negative carbon balance caused by the net effect of the harvest-associated carbon debt (strong negative impact) and net avoided emissions (positive impact) turns positive over time as biomass regrows and carbon is sequestered (figure 9), resulting in the carbon debt payback shown in figure 10 and discussed below. When assuming the second temporal perspective, carbon debt payback times of using wood pellets for bioelectricity were always zero years.

Note that the system carbon effect was calculated in this study (see figure 9), expressed as tonne carbon per MWh electricity produced (rather than for instance per hectare of forest). The carbon effect *of producing electricity* from wood pellets was determined over time. This allowed for fair comparison of wood pellet feedstocks (and their counterfactuals in the next section), as described in the methodological approach section of chapter 2.

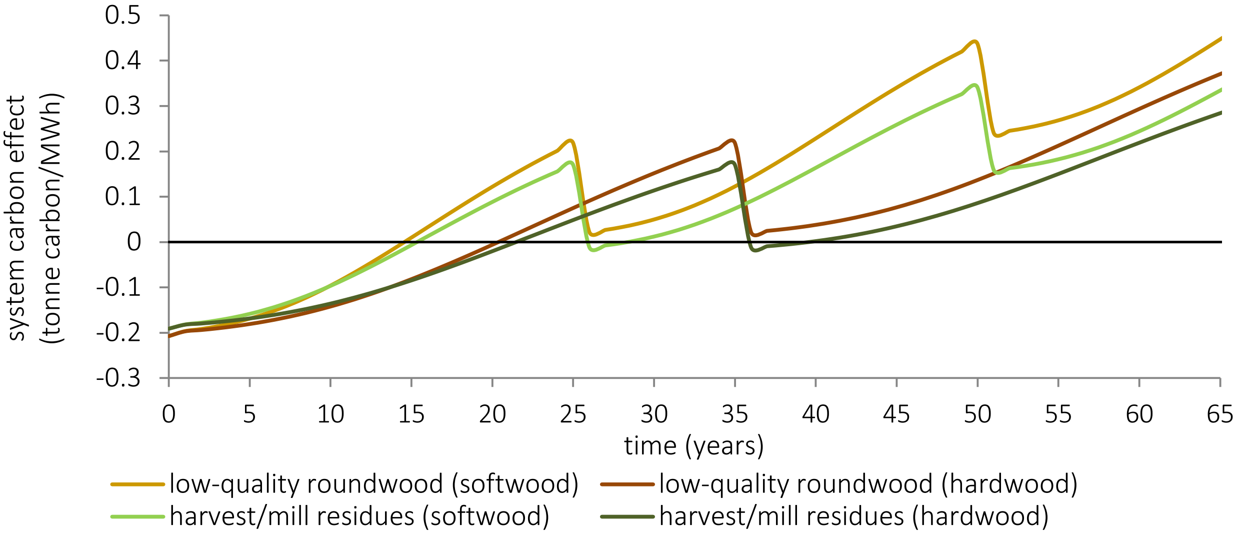


Figure 9. *Carbon balances of using wood pellets from different feedstock for bioelectricity. The initial carbon debt of electricity from wood pellets is repaid when the system carbon effect is zero, from this point on using wood pellets is better in terms of carbon than electricity production from coal.*

When applying the first temporal perspective, wood pellets from both harvest residues and mill residues had the longest (default) carbon debt payback times of 16 and 22 years for soft- and hardwood, respectively (figure 10; annex IV table 11). Carbon debt payback times of pellets from roundwood were slightly shorter, at 15 and 21 years for soft- and hardwood, respectively. The small difference in carbon debt payback times of pellets from roundwood and from harvest or mill residues was caused by the bark that is part of the roundwood feedstock. It replaces fossil fuels efficiently in year zero and increases the *absolute* amount of carbon that is stored over time per amount of electricity produced with pellets[80] (see figure 9). Thinnings were assumed to be purely additionally generated biomass without a harvest-associated carbon debt (see section 2.1); their use for wood pellets resulted in immediate carbon benefits and a carbon debt payback time of zero years. The underlying assumption (see section 2.1) is crude though; in reality thinning could lead to carbon debt and payback times larger than zero (i.e. a few years; further discussed in chapter 4). Except for thinnings, the larger differences among feedstock types lie in the counterfactuals and therefore in the wood pellets' carbon *parity* payback times more so than carbon *debt* payback times.

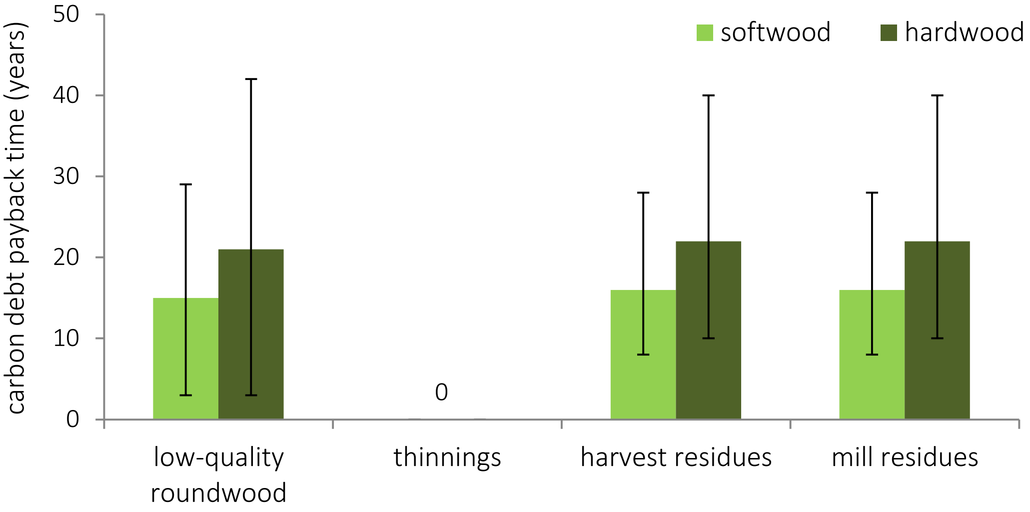


Figure 10. *Carbon debt payback times of wood pellets used for bioelectricity from different feedstocks. Error bars indicate the shortest and longest possible carbon debt payback times based on the parameter ranges found in this study.*

The type of tree used to produce pellets (i.e. softwoods or hardwoods) had a distinct effect on carbon debt payback times. Softwoods have shorter rotation periods and grow faster, which resulted in shorter carbon debt payback times found for all feedstocks except thinnings (figures 9 and 10). For thinnings the tree type distinction did not affect the outcome, as debt payback time was always zero.

The minimum and maximum carbon debt payback times (error bars in figure 2; table 11 and figure 15 in Annex IV), represent the shortest and longest possible payback times based on the parameter ranges found in this study (see sections 2.2-2.4 and 2.6). They are the most extreme and least likely[81] carbon debt payback times, as all other combinations of parameter values (within their ranges) yielded payback times closer to the default values displayed in figure 10. However, the minimum and maximum values pointed out that the uncertainty of exact carbon debt payback times is still considerable. Maximum carbon debt payback times were similar across all feedstock types (see table 11 in Annex IV), except thinnings (which have no maximum values). Minimum carbon debt payback times were shorter for pellets from low-quality roundwood than for pellets from residues. This difference was caused by the relatively large amount of avoided emissions in year zero of pellets from roundwood (due to bark replacing fossil fuels), which form an even larger share when assuming the maximum value for net avoided emissions.

---

[80] Roundwood pellets have a larger (harvest-associated) carbon debt, mostly due to the bark that is extracted from the environment, but does not end up in wood pellets. The larger debt is compensated for by high additional avoided emissions of bark replacing fossil fuels for heat production at mills. This results in roughly the same initial carbon balance for pellets from roundwood as for pellets from harvest and mill residues (figure 9). The regeneration rate of roundwood and both residues is the same. The *absolute* amount of regenerated biomass however, is higher for roundwood, because bark is included, resulting in slightly shorter payback times (figure 9); the shorter payback time of roundwood pellets found in this study can thus be attributed to the relatively efficient (local) use of bark and the relatively large amount of avoided emissions it causes.

[81] This holds even when each value in the parameter range is equally likely, but even more so when assuming that parameter values closer to the default parameter value are more likely.

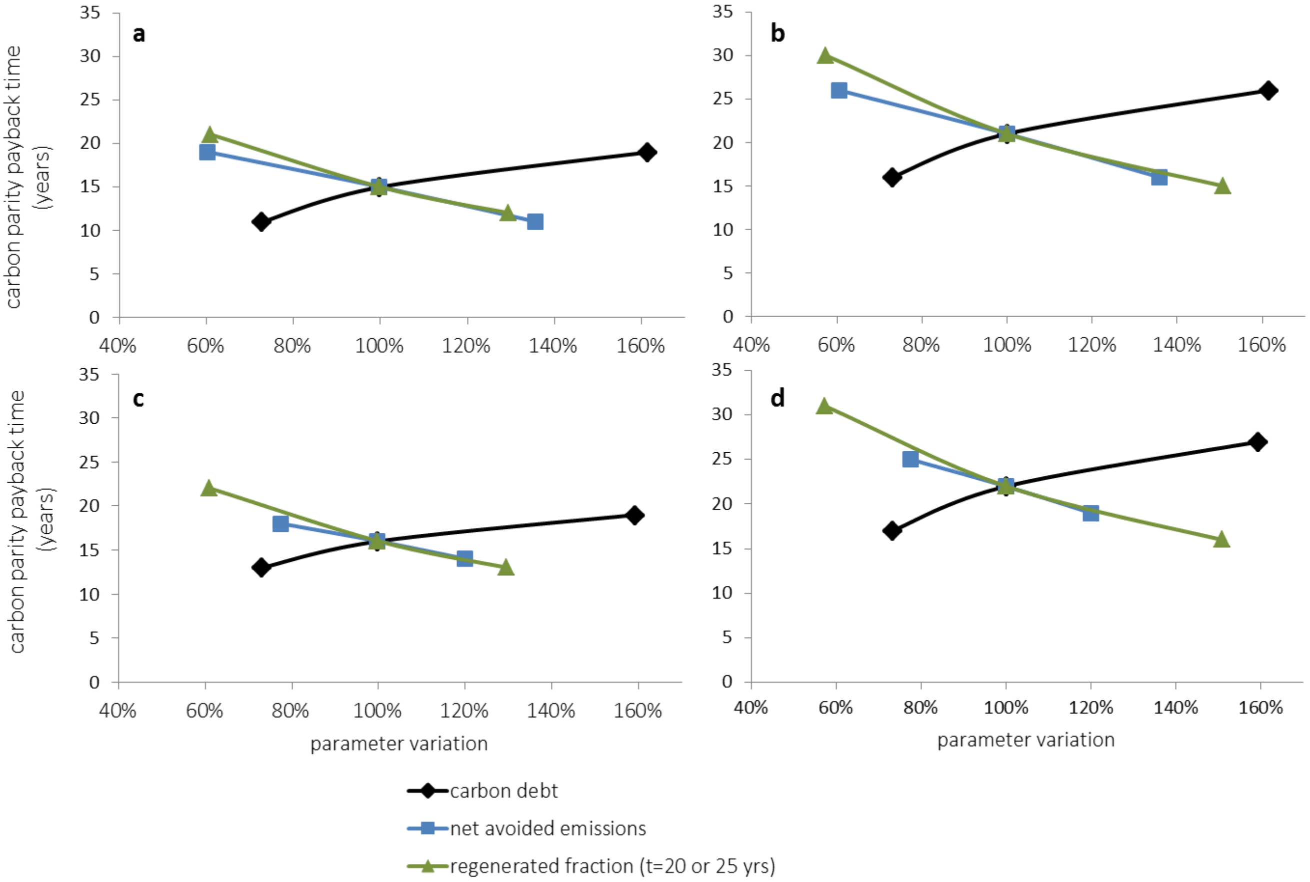


Figure 11. *Sensitivity analyses of carbon debt payback times for the size of the carbon debt, the amount of net avoided emissions and the regeneration rate. Regeneration rate was measured as the regenerated fraction at the amount of years equal to the shortest rotation period (20 years for softwood, 25 years for hardwood). Sensitivity analyses are shown for carbon debt payback times of:* **a)** *wood pellets from low-quality roundwood (softwood);* **b)** *wood pellets from low-quality roundwood (hardwood);* **c)** *harvest residues and mill residues (softwood);* **d)** *harvest residues and mill residues (hardwood). Note that values for harvest residues and mill residues were exactly the same.*

A sensitivity analysis was performed for pellets from low-quality roundwood and from harvest and mill residues, but was not required for thinnings or when applying the second temporal perspective[82]. The sensitivity analysis showed that a larger carbon debt increases carbon debt payback times, while higher net avoided emissions and a higher regeneration rate decrease carbon debt payback times (figure 11). All three components had a similar *relative* impact on carbon debt payback times, meaning that for instance a 10% increase in each component had an equally large effect on the payback times (as shown by the similar slopes of the different components in the spider diagrams of figure 11, the carbon debt has a reversed effect compared to the other components). For low-quality roundwood all three components were also roughly equally important in absolute terms (figure 11a, b), i.e. when looking at the entire parameter variation found here. For harvest and mill residues variation in net avoided emissions was lower, resulting in a somewhat weaker absolute effect on carbon debt payback times (figure 11c, d). This pattern was the same for both soft- and hardwood.

---

[82] When considering the second temporal perspective or thinning feedstock in general, carbon debt payback times are zero.

Carbon parity payback times

Carbon parity payback times were the result of both the factual carbon balance and the counterfactual (figure 12), because carbon parity is reached when the factual has a more positive carbon balance than the counterfactual (figure 13; this figure gives graphs for softwood; hardwood graphs are similar, see annex IV figure 16). The payback times strongly depended on the counterfactual assumed, as indicated by the large variation in payback times across different counterfactuals (figure 12, annex IV table y). Carbon parity payback times were less dependent on feedstock type itself, other than via the counterfactuals that apply to that feedstock (figures 12 and 13). The reason being that (factual) carbon balances of using wood pellets from different feedstocks were similar (see previous subsection and figure 13 black lines). This also held for thinnings, when comparing them to carbon balances of wood pellets from other feedstocks in the second temporal perspective[83] (figure 13b,c,e,g; black lines). The counterfactuals relevant for thinnings all result in short carbon parity payback times of wood pellet bioelectricity from thinnings; other feedstock types are associated with at least one counterfactual that leads to longer carbon parity payback times (figure 12). Results of the effect specific counterfactuals types on carbon parity payback times are presented below, including the minimum and maximum payback times (again, default values were more likely[84]). After looking at counterfactuals, the influence of tree type (softwood/hardwood) and temporal perspective is shown.

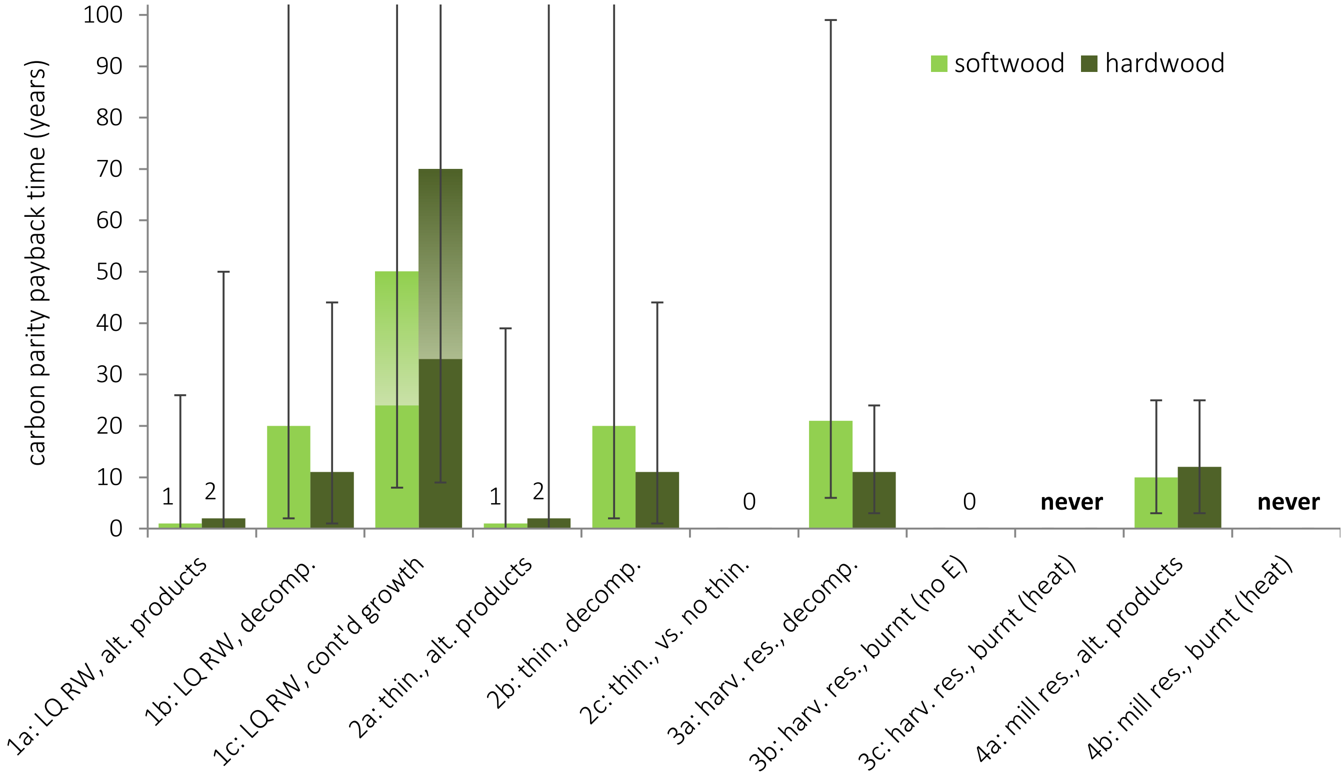


Figure 12. *Carbon parity payback times of wood pellets (used for bioelectricity) from different feedstocks (1-4) and assuming different counterfactual scenarios (a-c) for full descriptions see section 2.5. Results are the same for temporal perspectives, except for counterfactual 1c, here the lower bars indicate carbon parity payback times assuming the first temporal perspective, and the higher bars the second temporal perspective. Error bars indicate the shortest and longest possible carbon parity payback times based on the parameter ranges found in this study (see sections 2.2-2.4 and 2.6 for these ranges and section 2.8 for minimum/maximum payback time calculations).*

---

[83] In almost all cases, temporal perspective did not influence carbon parity payback times, as explained below.

[84] Minimum and maximum payback times are exceptional cases based on the most extreme parameter values in this study. They are the least likely results, as all other combinations of parameter values (within their ranges) yield carbon payback times closer to the default payback times. This holds when each value in the parameter ranges is equally likely, and even more so when parameter values closer to default parameter values are more likely.

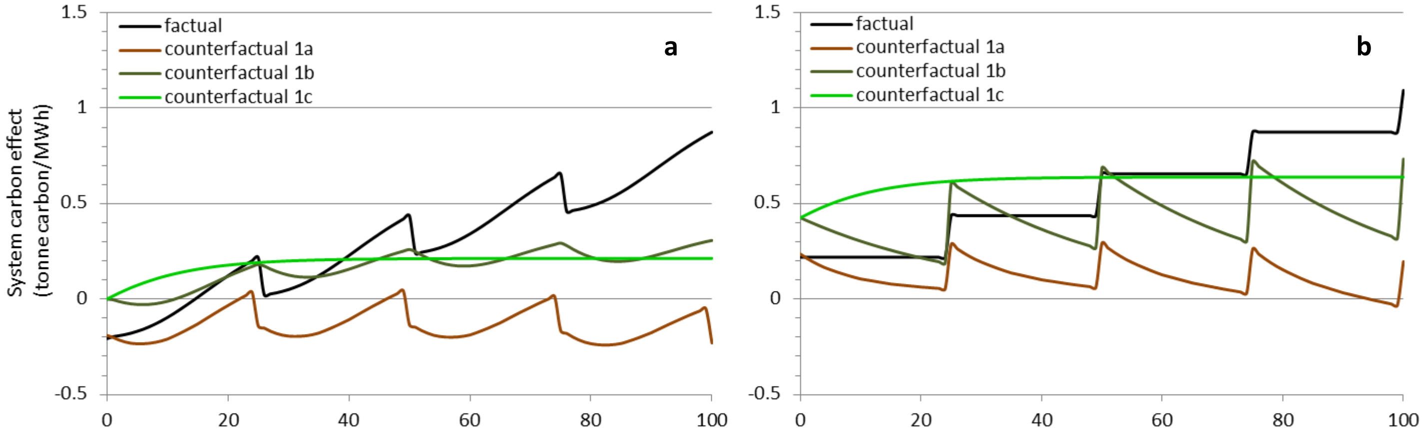
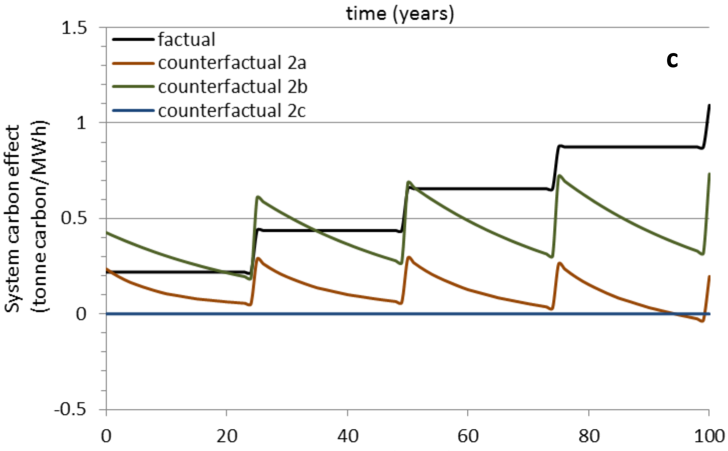
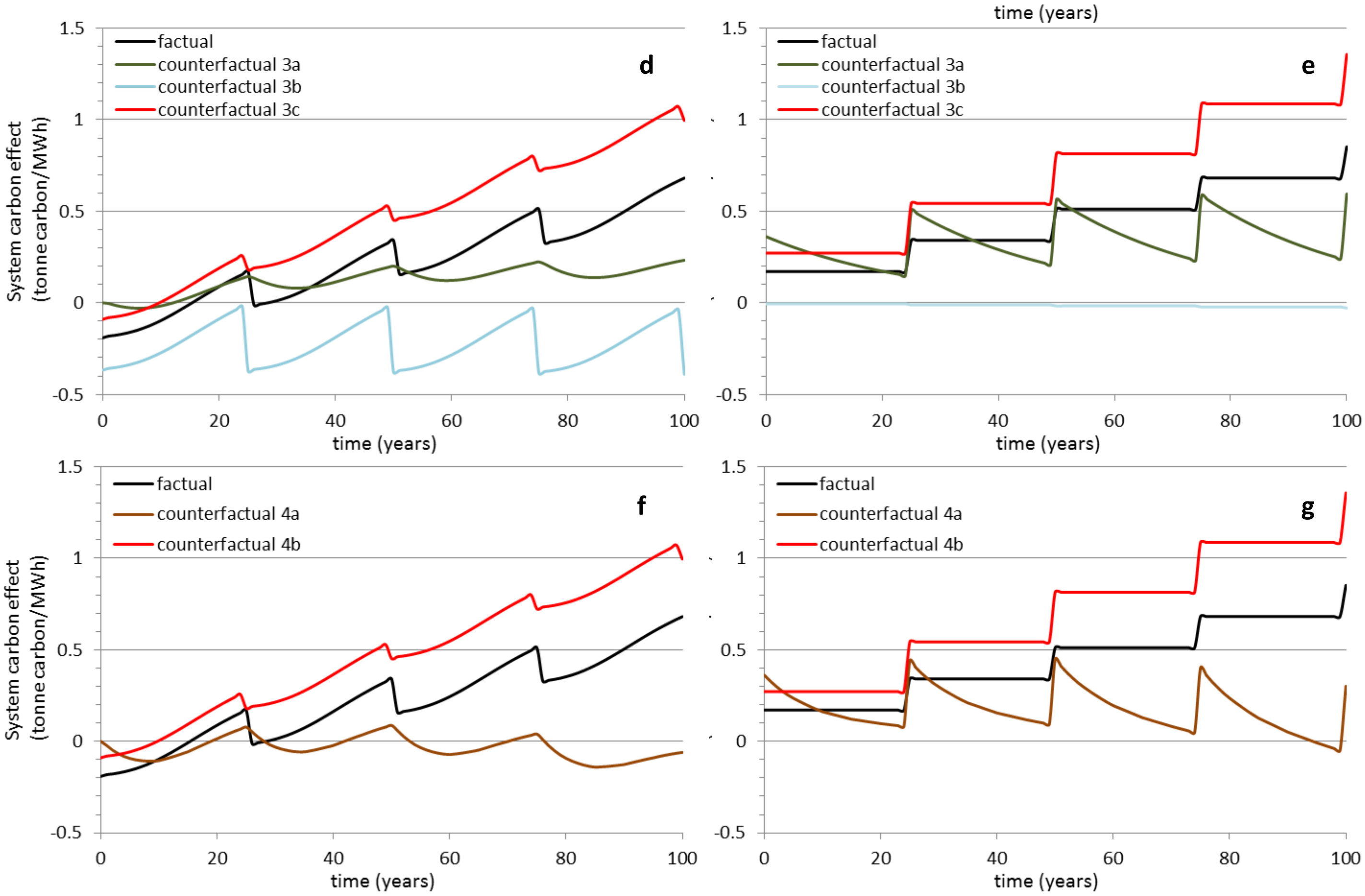


Figure 13. *Carbon balances of wood pellets used for bioelectricity production from hardwood feedstocks (factuals) and their counterfactual. Figures:* ***a)*** *and* ***b)*** *low-quality roundwood 1st and 2nd temporal perspective respectively;* ***c)*** *thinnings;* ***d)*** *and* ***e)*** *harvest residues 1st and 2nd temporal perspective, respectively;* ***f)*** *and* ***g)*** *mill residues 1st and 2nd temporal perspectives, respectively. For descriptions of counterfactuals see section 2.5.*





Counterfactuals in which the feedstock is used to produce forest products (1a, 2a and 4a) resulted in relatively short carbon parity payback times (figure 12). In counterfactuals 1a and 2a, 45% of biomass is burned in year zero (without energy capture or while providing energy for forest product manufacturing). Moreover in the first few years a large fraction of the carbon in forest products is released (mainly through decomposition and burning of paper and other short-lived products). These two effects resulted in short parity payback times of 1 or 2 years for wood pellets used for bioelectricity that are compared with counterfactuals 1a and 2a. In counterfactual 4a no biomass is burned in year zero[85] , which lead to carbon parity payback times of about a decade. Minimum carbon parity payback times for wood pellets compared to this counterfactual type were zero, i.e. instant carbon benefits. Maximum carbon parity payback times in these three cases were several decades (for softwood) up to more than a century (for hardwood) or are even never reached (in case of counterfactual 4a; see figure 17 in annex IV). In these maximum cases, landfills were assumed not to emit methane and for a long time (or for 4a even indefinitely), hence forming a more effective carbon storage than avoiding fossil emissions (in the factual scenario) can make up for. It must be noted that landfills in fact would emit methane and that these maximum payback times are extreme and less realistic. However it is clear that carbon parity payback times were sensitive to assumptions here.

Counterfactuals in which the feedstock is left to decompose (1b, 2b, 3a), all resulted in similar and relatively short carbon parity payback times, of 20-21 years for softwood and eleven years for hardwood. These three counterfactuals crossed the factual carbon balance more than once, correcting for this would result in parity payback times of about a decade longer[86]. Again there was large variation when looking at the minimum and maximum values (minima range from one to six years; maxima range from 24 to over 100 years), but carbon parity was always reached, and as explained above maximum and minimum values are less likely than values closer to the default values. Minimum and maximum decomposition were quite well known (see section 2.6) and do not vary substantially and therefore hardly affected carbon parity payback times (see figure 14a and b), here the factual and counterfactual were simply quite similar (see figure 13a-e), and variation in carbon debt and net avoided emissions could make a large difference in parity times (see figure 14a, b).

The continued growth counterfactual (1c) for the low-quality roundwood feedstock resulted in relatively long carbon parity payback times (figure 12): 24 and 33 years for soft- and hardwood respectively when assuming the first temporal perspective, and 50 and 70 years for soft- and hardwood when assuming the second. Growth dynamics that are part of the first perspective, but not the second, resulted in shorter carbon parity payback times for the first perspective. When assuming the first temporal perspective, a temporary peak in the carbon balance of the factual crossed the carbon balance of the counterfactual (compare figures 13a and 13b). Correcting for this temporary peak (i.e. adding the time interval in which the factual balance dips below the counterfactual balance to the payback time) resulted in carbon parity payback times under the first temporal perspective of about 40 and 55 years for softwood and hardwood respectively (see figure 13b and see annex IV figure 16b). The remaining difference between the payback times found under the different temporal perspectives can be attributed to growth dynamics that are included when assuming the first perspective. Minimum and maximum values again varied substantially (see annex IV table 12b), depending most on carbon debt, net avoided emissions and growth rate (see figure 14c).

---

[85] See section 2.6, mill residues can entirely be used to produce forest products, whereas roundwood and thinnings have non-usable fractions (e.g. bark).

[86] The carbon balance of wood pellets used for bioelectricity and counterfactuals sometimes cross multiple times (see figure 13): beyond the parity point the counterfactual temporarily has more positive balance. Usually this is brief and the general effect stays the same. Though temporary, it is good to notice that the carbon parity payback time does not imply that the factual carbon balance is *always* more positive from the payback time onwards. For the decomposition counterfactuals 1b, 2b, 3a there is a stretch of time of nearly a decade beyond the carbon parity point where the counterfactual temporarily has a more positive carbon balance. One could therefore argue that their “averaged” carbon parity payback time would be about a decade longer than the default values reported above.

Using wood pellets from thinnings to produce bioelectricity always resulted in a more positive carbon balance than not thinning at all (counterfactual 2c). Because this counterfactual had a constant carbon balance of zero, carbon parity times were equal to the carbon debt payback times and both payback times were zero under the assumptions of this study (see section 2.1 for assumptions on thinnings; further discussed in chapter 4).

Burning harvest residues without energy capture (counterfactual 3b) always resulted in a lower carbon balance than using harvest residues to produce pellets that are used for electricity generation. On the other hand, using harvest residues (counterfactual 3c) or mill residues (counterfactual 4b) to provide heat at (local) mills (e.g. paper mills) always resulted in a more positive carbon balance than using harvest or mill residues for wood pellet- and ultimately electricity production. These results were the same, regardless of temporal perspective and tree type, and when trying all possible combinations of minimum and maximum parameter values.

The carbon balances of most hardwood (feedstock) counterfactuals had a similar pattern as the counterfactuals of softwood (compare figure 13 above and figure 16 in annex IV). Main differences between softwood and hardwood were the longer rotation period and lower growth rate of hardwood (modeled here via the regeneration rate). Slower regeneration of hardwood affected both factual and counterfactual, ultimately slowing both balances down and resulting in longer carbon parity payback times for hardwood. One exception was formed by the natural decomposition counterfactuals (1b,2b,3a). Here, relatively quick decomposition of hardwood (faster than for softwood) meant that little carbon was stored in these hardwood counterfactuals. The carbon balance of using (hardwood) wood pellets for bioelectricity thus surpassed the decomposition counterfactuals relatively soon, resulting in shorter carbon parity payback times of hardwood pellet bioelectricity.

In almost all cases the temporal perspective did not affect the ultimate carbon parity payback times (figure 12; table 12 in annex IV). Exceptions were counterfactual 1a (higher maximum parity times in the second temporal perspective) and 1c (higher default and minimum parity times in the second temporal perspective, due to growth dynamics included in the first temporal perspective as explained above). This result is in contrast to results on carbon *debt* payback times of wood pellet bioelectricity, for which the second temporal perspective (reference carbon stocks are determined when trees start growth) always resulted in shorter carbon debt payback times (of zero years). The reason that assuming the second temporal perspective did not affect carbon *parity* payback times in most cases (whereas it did for carbon *debt* payback times) is that this temporal perspective had to be applied to both the factual and the counterfactual. This meant that both the factual and counterfactual started out with a more positive carbon balance. Ultimately this resulted in the same carbon parity payback times, regardless of the temporal perspective assumed (or for the two exceptions described above: somewhat longer payback times in the second temporal perspective).

A sensitivity analysis was performed for the effect of carbon debt, net avoided emissions, regeneration rate and the carbon emission of the counterfactuals on carbon parity payback times. Figure 14 shows the results of the sensitivity analysis for four representative cases (different feedstocks, tree types, temporal perspectives and counterfactual types). First of all, the effect of carbon emission in the counterfactuals was limited. This may seem in contrast to previous results. It is important to note that the choice of counterfactual was crucially important for the carbon parity payback times (as illustrated by figure 12). However, once the type of counterfactual and therefore the basics of its entire emission pattern was chosen, the effect of varying the exact emissions somewhat was similar to the other components (as can be noted in figure 14: the emitted fraction curve has a slope that is usually similar to that of the net avoided emissions and the [reversed] carbon debt). Moreover, the variation in the emitted fraction was limited based on the assumptions made in section 2.6, as can be noted from the small *absolute* effect that emitted fraction has on carbon parity payback times. When assuming the firs temporal perspective, carbon debt had the largest effect on carbon parity payback times, as it scaled the counterfactual and is part of the factual (figure 14a,b,d). When assuming the second temporal perspective net avoided emissions were most important (figure 14b), as carbon debt was not part of the factual scenario in this perspective (see section 2.8). Regeneration rate was relatively unimportant in most cases. When asusming the first temporal perspective regeneration affected factual and counterfactual in the same way; one exception is counterfactual 1c, in which regrowth was replaced by continued growth (modeled via a 'negative emitted fraction'). When assuming the second temporal perspective, regeneration was not modeled. An important final note is that sensitivity analyses were based on the default, minimum and maximum values of each component only (as depicted by the dots on the curves in figure 14), a continuous sensitivity analysis may expose parameter value thresholds. In general, carbon parity payback times are more sensitive to the assumed underlying parameters ranges than carbon debt payback times, this predominantly caused by scaling of the counterfactuals with the carbon debt.

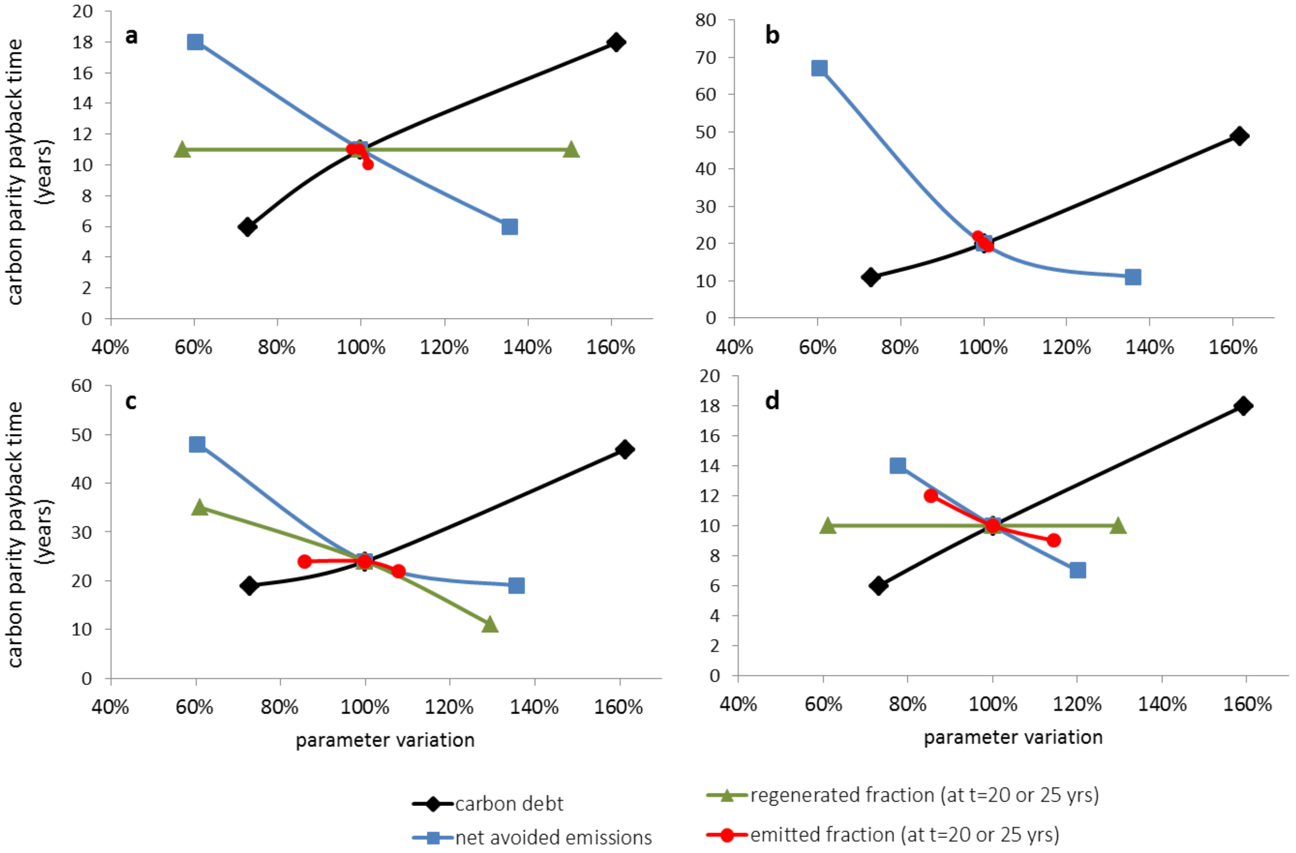


Figure 14. *Sensitivity analyses of carbon parity payback times for the size of the carbon debt, the amount of net avoided emissions, the regeneration rate and the carbon emission in the counterfactual. Note that y-axes are differently scaled (to enhance readability). Regeneration rate was measured as the regenerated fraction at the amount of years equal to the shortest rotation period (20 years for softwood, 25 years for hardwood). Similarly, carbon emission in the counterfactual was measured as the emitted fraction at 20 and 25 years for soft- and hardwood, respectively. Sensitivity analyses are shown for:* **a)** *wood pellets from low-quality roundwood and counterfactual 1b for hardwood in the first temporal perspective;* **b)** *wood pellets from low-quality roundwood and counterfactual 1b for hardwood in the second temporal perspective;* **c)** *wood pellets from low-quality roundwood and counterfactual 1c for softwood in the first temporal perspective (note that a higher "emitted fraction" in this counterfactual means a higher sequestered fraction);* **d)** *wood pellets from mill residues and counterfactual 4a for softwood in the first temporal perspective.*

4. Discussion

Carbon debt payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US are very similar when the wood pellet feedstock is low-quality roundwood, harvest residues or mill residues. In these cases carbon debt payback times are 15 to 16 years for softwood and slightly longer at 21 to 22 years for hardwood. The range of minimum and maximum values is substantial, though default values are far more likely; *minimum* payback times are shorter if low-quality roundwood used as feedstock compared to using residues. These results are obtained when reference carbon stocks are determined just before harvesting (i.e. when assuming the first temporal perspective). Carbon debt payback times of *zero* years are always obtained if the reference carbon stocks are determined at the moment trees start growth (i.e. when assuming the second temporal perspective). When thinnings are used as wood pellet feedstock, calculated carbon debt payback times of wood pellet bioelectricity are always zero, regardless of temporal perspective (further discussed below).

Carbon parity payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US vary strongly, depending on the counterfactual scenario assumed. What counterfactuals are assumed in turn depends on the wood pellet feedstock type. Wood pellet feedstock itself does not strongly affect carbon parity payback times (other than via the choice of counterfactual). The counterfactuals relevant for thinnings all result in short carbon parity payback times of wood pellet bioelectricity from thinnings; other feedstock types are associated with at least one counterfactual that leads to longer carbon parity payback times.

In this study, counterfactuals in which the feedstock is used to produce traditional forest products and counterfactuals in which the feedstock is left to decompose result in short carbon parity payback times (default values of 1-12 and 11-21 years respectively) and show a relatively large spread in minimum and maximum values. Counterfactuals in which wood pellet feedstock is burnt to provide heat (locally) rather than being converted into wood pellets for (transatlantic) bioelectricity production always have a more positive carbon balance, meaning that carbon parity is *never* reached. The continued growth counterfactual for low-quality roundwood feedstock results in relatively long payback times (corrected [see results] default values of about 40-70 years). Calculations on using wood pellets from thinnings to produce bioelectricity result in instant carbon parity (payback times of zero years) when compared to the counterfactual of not thinning at all. The counterfactual of burning harvest residues without energy capture also results in carbon parity payback times of zero years.

Wood pellet feedstocks originating from softwoods generally result in shorter carbon parity payback times of wood pellet bioelectricity, due to faster growth of softwoods. The exception is arises when the counterfactual scenario is decomposition of the feedstock: as hardwoods decompose faster, parity payback times of wood pellet bioelectricity are in this case shorter for hardwood feedstock.

In almost all cases, the temporal perspective assumed does not influence carbon parity payback times of electricity using wood pellet (one exception is the continued growth counterfactual, where growth dynamics cause shorter parity payback times in the first temporal perspective). The second temporal perspective had to applied to both factual and counterfactual, which both started out with a more positive carbon balance, ultimately resulting in the same carbon parity payback times as under the first temporal perspective. In contrast to results on carbon *debt* payback times, the second temporal perspective does not result in shorter carbon *parity* payback times of wood pellet bioelectricity.

The sensitivity analyses of both carbon debt and parity payback times showed that no *single* component (carbon debt, net avoided emissions, regeneration or counterfactual carbon balance) was most important for the final carbon payback times. This indicates that carbon debt and parity payback times calculated in this study do not hinge on a few assumptions of one component, but rather, more solidly on the entire methodology.

The range of minimum and maximum payback times found in this study was large for some carbon debt payback times and most carbon parity payback times of wood pellet bioelectricity. Exceptions are cases in which carbon debt or parity payback times were zero, or when carbon parity was never reached. In these cases all possible parameterisations (within the parameter ranges identified in this study) yielded the same results, meaning that these results are robust. Coming back to cases with large minimum/maximum ranges: the default payback times of these cases are more uncertain. The uncertainty is smaller however, than it may seem based solely on the minimum/maximum intervals. As briefly mentioned in the results section, default payback times are more likely outcomes than minimum and maximium values. Minimum and maximum payback times are exceptional cases based on the most extreme parameter values in this study. They are the least likely results, as all other combinations of parameter values (within their ranges) yield carbon payback times closer to the default payback times. This holds when each value in the parameter ranges is equally likely, and even more so when parameter values closer to default parameter values are more likely. The latter is often the case (to illustrate this consider some examples of unlikely situations that minimum/maximum parameter values were based on: e.g. no methane emissions from landfills at all, not using any bark for providing heat – or on the other hand using all bark to replace coal only, etc.). Ultimately, for those cases with large minimum/maximum payback time ranges, results are less robust and could be seen as strong indications, rather than outspoken results.

The results that feedstock type has a limited effect on carbon debt payback times (except for thinnings, discussed below) and a limited effect on carbon parity payback times (other than via the choice of counterfactual) can partially be explained by the approach of this study. It was decided in this study to assign a carbon debt to residues, as their embodied carbon was extracted from the environment at some point. It could also be argued that they do not have a carbon debt and that any debt should be fully allocated to the primary products (e.g. timber), not the *residues.* In this study on the other hand, the characteristics of the wood pellet feedstock were predominantly covered by the counterfactuals (e.g. harvest residues may be burnt as waste, whereas roundwood would not be burnt as waste). This approach is sensible, because what makes feedstock types fundamentally different in terms of their carbon balances is what would have happened to the material if it had not been used as wood pellet feedstock. The most relevant material properties, such as carbon content, are actually similar for all feedstock types. The amount heat required for feedstock drying and the exact energetic content of different wood pellet feedstocks are two properties that were not included in this analysis[87] and that could make a difference. They would likely elongate payback times of wood pellet bioelectricity with harvest residues as pellet feedstock, because this feedstock is relatively wet. Overall, the result that counterfactuals are more decisive than feedstock type itself for carbon parity payback times is partly explained by the approach of this study, but it is a sensible approach.

The two temporal perspectives on determining reference carbon stocks that were investigated in this study were based on fundamentally different views on carbon accounting that are implicitly assumed or explicitly stated in previous studies (see box 2). The two perspectives were approached with different calculations (see research overview subsection, page 10) and yielded different carbon balance patterns (compare figure 13a,d,f and 13b,e,g). They resulted in different carbon debt payback times of wood pellet bioelectricity. Considering these differences, the fact that the two perspectives resulted in *the same* carbon parity payback times, is a real result and not an artefact of calculations. The exception formed by the continued growth counterfactual, for which the second temporal perspective results in longer parity payback times, further confirms the rule that the temporal perspectives are fundamentally different, but in almost all cases yield the same carbon parity times.

Carbon debt payback times of wood pellet electricity with thinnings as pellet feedstock were always zero in this study. This result strongly depends on the assumption that thinnings are purely

---

[87] Note that the effect of drying on carbon content and mass of feedstock was included, but the amount of heat required for drying was not differentiated over feedstocks.

additionally generated biomass (see section 2.1). This assumption was made to account for the fact that when forests are thinned, forest growth increases, usually leading similar or even larger final biomass harvests compared to a situation without thinning (as is well-documented in section 2.1). However, the assumption did not account for the fact that when a forest is thinned, carbon stocks are temporarily lowered. Thus, when thinnings are used as pellet feedstock and the first temporal perspective is considered, carbon debt payback times have to be larger than zero. Carbon debt payback times would still be substantially lower than when considering other wood pellet feedstocks, because of the enhanced growth due to thinning, which is large enough to (more than) compensate all extracted biomass during thinning. As forests are usually thinned in mid-rotation (see for example Jonker et al., 2013), and thinning thus compensates its own biomass loss within half a rotation period, a very rough first estimate of carbon debt payback times would be that they are about half of payback times obtained when using roundwood as pellet feedstock.

The continued growth counterfactual for roundwood feedstock is comparable to the protection scenario of earlier studies (see annex I). This counterfactual resulted in relatively long carbon parity payback times, i.e. the counterfactual has a more positive carbon balance for a long period of time. In this counterfactual however, forests have to remain unharvested in order to have a more positive carbon balance. This may prove difficult to guarantee over periods of time in the order of the carbon parity payback time (i.e. around 40-70 years into the future). In case forests are harvested earlier, carbon parity would be reached earlier as well.

For counterfactuals 1b, 1c, 2b, 3a the counterfactual and factual carbon balances cross each other multiple times (figure 13a-e), this can roughly be corrected for by adding the time interval in which the factual balance dips below the counterfactual balance to the payback time. This resulted in carbon parity payback times of about a decade longer in these cases (as described in the results section).

In this study the carbon balance of wood pellet bioelectricity was studied per amount of electricity produced (i.e. the changes in stored carbon caused by the production of an amount of electricity were tracked over time). This is a different approach from most carbon accounting studies (e.g. all studies in annex I), in which carbon storage and flows are tracked per hectare of forest. Carbon payback times found in this study for scenarios investigated in previous studies (e.g. roundwood as feedstock, forest protection and continued growth as counterfactual) did not differ much from payback times found in those earlier studies (discussed below). This supports validity of this approach. The approach used was also required to answer this study's main research question, as it allowed better comparison of different wood pellet feedstock types (an hectare of forestland does not produce equal amounts of each feedstock, whereas the amounts of feedstock required for a certain amount electricity can be calculated directly). An advantage of the approach used here is that downstream value chain emissions as well as avoided emissions can be easily and directly attributed to an amount of electricity (similar to life cycle assessment studies, e.g. Sikkema et al., 2010; Dwivedi et al., 2014; see table 4 on page 30). In light of Using wood pellets to generate bioelectricity is a result of European policy. A second advantage of this study's approach is the fact that carbon effects of producing bioelectricity in Europe (rather than the carbon effects of using American forestland for one purpose or another) are of interest to European policymakers. Estimated carbon effects of using bioelectricity can be determined at any point in time.

Belowground carbon and all other non-tree ecosystem carbon stocks (understory, dead wood, etc.) were assumed to stay constant (for reasons explained in section 2.2). Harvest residues were not included in the carbon debt of low-quality roundwood and thinnings (explained in section 2.2). No land-use change (LUC), indirect land-use change (iLUC) and indirect wood use change (iWUC) were included in this study (for reasons explained in detail in the methodological approach subsection on page 13). If, however, these effects were included in the analysis, or if the non-tree ecosystem carbon pools were to decrease due to tree harvesting, the size of the carbon debt of wood pellets used for bioelectricity would increase. This would ultimately result in longer carbon debt and parity payback times of wood pellet bioelectricity.

The exact parameterisations of the regeneration rates in this study were based on obtaining 100% regeneration at the end of the rotation period (obtained from literature), while at the same time maximising average annual biomass increase (as was assumed in previous studies), and having a growth curve pattern that is qualitatively similar to previous studies (see section 2.3 for details). This approach resulted in growth curves that were similar to earlier work (e.g. Jonker et al., 2013) and are likely to be fairly accurate. However, forest *growth rates* based on empirical data may have resulted in somewhat different *regeneration rates* - faster or slower. Furtheremore, the assumption that harvesting takes place to maximise biomass production may not always hold (e.g. for small-landowners, see box 1), resulting slower average growth (over the landscape). Since the regeneration rates used here were still similar to previous studies and since a wide variation between minimum and maximum values was assumed, it is unlikely that regeneration rates outside of the minimum/maximum range found here would be obtained. Moreover, though carbon *debt* payback times are relatively dependent on regeneration rate, carbon *parity* payback times are not strongly influenced by regeneration rates at all (as shown by the sensitivity analysis), as both factual and counterfactual are affected in a similar way (except for continued forest growth counterfactual).

The wood pellet value chain considered in this study was based on wood pellets from the US South-East that are used to generate electricity in the Netherlands. Many aspects of this study were strongly US South-East specific (e.g. early value chain emissions, choice of feedstocks, choice and quantitative specifics of counterfactuals, etc.). On the other hand, only the downstream value chain emissions and the avoided emissions from replacing coal were based on wood pellet use in the Netherlands. Results of this study are probably only valid when taking the US South-East as sourcing area. However, results of this study may also hold for different target areas than the Netherlands, as long as approximate shipping distance and the fossil fuel replaced (i.e. coal) are the same (which form by far the most determining factors of the Netherlands-specific side of this study).

Carbon payback times found in this study are similar to those in previous studies that looked pellets from the US South-East, when assuming the same characteristics (feedstock, temporal perspective, counterfactual etc.). The default carbon debt payback time of wood pellet bioelectricity from softwood roundwood under the first temporal perspective was 15 years in this study. Similar to the 5-11 (single stand level) and 12-18 (increasing stand level) year debt payback times found by Jonker et al. (2013) for wood pellet bioelectricity (replacing coal) with whole trees from pine plantations as pellet feedstock. Default carbon parity payback times of wood pellet bioelectricity from roundwood assuming a continued growth counterfactual were 40-70 years in this study (40 is a corrected value, as explained above). Similar to the 28-80 year (Jonker et al., 2013) and 35-50 year (Colnes et al., 2012) ranges that were found while assuming the same counterfactual (no additional harvesting, or: protection) and other general characteristics.

In general, the range of carbon debt and parity payback times found in this study fit within the wide range of carbon payback times of wood pellet bioelectricity found across different biomes (see annex I). One exception are formed by the counterfactuals in which harvest or mill residues are burnt to provide heat, in these cases carbon parity is *never* reached; a result that has not been found before to the author’s knowledge (see also annex I).

The choice of wood pellet feedstock type affected carbon payback times of wood pellet bioelectricity in this study mostly via the resulting choice of counterfactual. In earlier studies it was found that if the counterfactual caused large GHG emissions in the short term (e.g. because it would quickly decompose or be burnt as waste), using it to produce pellets results in short carbon parity payback times or even instant carbon parity (McKechnie et al., 2011; Zanchi et al., 2012; Bernier & Paré, 2013; Lamers et al., 2013a, 2014b). Lamers et al. (2014b) found that harvest residues that would otherwise be burnt result in carbon parity payback times of zero years; this is exactly what was found in this study (counterfactual 3b). Zanchi et al. (2012) found that harvest residues yielded short carbon parity payback times compared to the counterfactual of leaving them to decompose (0-16 years depending on the fossil fuel replaced); in this study default values of 11-21 years were found for this counterfactual (i.e. counterfactual 3a). Mckechnie et al., (2011) found carbon parity payback times of wood pellet bioelectricity (assuming a counterfactual of traditional harvests only; see annex I) are 16 years for harvest residues and 38 years for roundwood. The difference was caused mostly by the size of the carbon debt (i.e. the amount of carbon extracted from the forest).

In line with the results of this study, Stephenson & MacKay (2014) found that using feedstock that would otherwise release GHG emissions in the short term to produce wood pellets for bioelectricity leads to a more favourable carbon balance than using fossil fuels. These authors also found that emissions from wood pellet electricity made from trees that would otherwise not been harvested (as frequently) are higher than the fossil alternative. This scenario is similar to the continued growth counterfactual for roundwood in this study (counterfactual 1c), which led to relatively long carbon parity payback times (default values of 40 to 70 years). Two studies found that using (hardwood) roundwood to produce wood pellets for bioelectricity results in higher emissions of fossil fuels for at least 40 to 50 years (Buchholz & Gunn, 2015; NRDC, 2015). This result is again similar to the result of this study that carbon parity payback time for hardwood roundwood are 55 to 70 years, assuming a continued growth (i.e. non-harvesting) counterfactual.

Some findings of this study do not have comparable previous results. Softwood resulted in shorter carbon payback times than hardwood in almost all cases as explained above. These tree types have not been explicitly compared in terms of their effect on carbon payback times of wood pellet bioelectricity. Similarly, the temporal perspectives, which had a large effect on carbon *debt* but not *parity* payback times, have not been compared explicitly before. Lastly, one of the key results of this research is actually formed by the new types of counterfactuals defined in this study. As outlined in section 2.5, counterfactuals were defined using input from forest and wood pellet stakeholders and experts (predominantly from the US South-East) and are thus likely to be realistic alternatives. Previous studies almost exclusively used counterfactuals that existed of not harvesting the wood pellet feedstock (e.g. protection scenarios, no additional harvesting scenarios, etc. see annex I). Counterfactuals in this study also included scenarios in which a potential wood pellet was used for other purposes (products manufacturing, providing heat). Furthermore, the effect of counterfactuals that included decomposition or burning of the potential wood pellet feedstock without energy capture on parity payback times was explicitly calculated here (rather than assuming instant carbon parity).

5. Conclusions

The findings of this study show that carbon *debt* payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US are similar when using low-quality roundwood, harvest- or mill residues as wood pellet feedstock. Using thinnings as feedstock results in short carbon debt payback times. When reference carbon stocks are determined at the moment trees start growth (rather than just before harvesting), carbon debt payback times of wood pellet bioelectricity are zero years, regardless of feedstock.

Carbon *parity* payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US vary substantially. Wood pellet feedstock itself hardly affects carbon parity payback times, but does determine what counterfactual scenarios are applicable. The counterfactual does strongly influence carbon parity payback times: when feedstock is left to decompose or used in traditional forest products carbon parity payback times are relatively short, when feedstock is not harvested at all carbon parity payback times are relatively long. Using feedstock material to provide heat locally results in carbon parity never being reached, whereas burning feedstock materials without energy capture results in instant carbon parity. The selection of counterfactuals used in this study was larger than previous studies and may better reflect reality.

Ultimately, results still have considerable uncertainty, but counterfactuals relevant for thinnings all result in relatively short carbon parity payback times and using thinnings as feedstock resulted in shortest carbon debt payback times of wood pellet bioelectricity. Thinnings may therefore form the best wood pellet feedstock type in terms of reducing GHG emissions of wood pellet bioelectricity.

Carbon *debt* payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US are likely to be shorter for softwood feedstock material than for hardwood feedstock material. The same holds for carbon *parity* payback times, except when the counterfactual consists of natural decomposition, in which case hardwood feedstock probably result in shorter payback times.

The temporal perspective on reference system carbon stocks very strongly influences carbon *debt* payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US. When reference carbon stocks are determined just before harvesting (first perspective) default debt payback times are in the order of one or two decades. When reference carbon stocks are determined when trees start growth (second perspective) debt payback times are always zero.

Surprisingly, in almost all cases the temporal perspective on reference system carbon stocks does not affect carbon *parity* payback times of bioelectricity generated in the Netherlands using wood pellets from the south-eastern US. Carbon parity times are probably the most realistic indicator of the point in time beyond which net greenhouse gas benefits start accruing (as they consider a counterfactual scenario). The results of this study thus suggest that temporal perspective should not substantially influence the outcome of the wood pellet bioelectricty's carbon balance and resulting policy decisions, as long as counterfactuals are properly accounted for.

Results of this study have some interesting potential implications, but considerable uncertainty as well, due to large parameter ranges; future research could try to narrow these ranges down. Findings in this study suggest that thinnings form an interesting wood pellet feedstock in terms carbon emissions, however results for thinnings were also had the highest uncertainty. The carbon balance of wood pellets (used for bioenergy) from thinnings specifically could be further investigated. One counterfactual scenario was considered at a time in this study. In reality, several counterfactual scenario may hold at the same time for one feedstock type. It would be interesting to create a mix of counterfactuals based for each feedstock (potentially depending on local conditions) in order to better compare the role of feedstock type. The result that temporal perspecitve does not influence carbon parity payback times is remarkable, and could be further tested in future studies.

To obtain a more complete picture on what feedstock types are favourable a wider assessment is required. This assessment could include economic viability and environmental concerns other than climate change mitigation (e.g. biodiversity, water quality, etc.). Furthermore, carbon dynamics could be modelled in more ecological detail, i.e. by including more complex carbon pool dynamics (belowground, dead wood, undergrowth), more realistic modelling of growth dynamics (including the effect of biophysical influences and forest management). The occurance and effects on wood pellet bioelecticity carbon payback times of land-use change (LUC), indirect land-use change, and indirect wood use change also require further investigation. Lastly, harvesting decisions affect the results of this study, the influence of landownership on harvesting decisions could be included in future studies on the carbon balance of wood pellet used for bioelectricity.

It is difficult to estimate carbon payback times of using wood pellets from the south-eastern US to produce (bio)electricity in the Netherlands. Carbon parity payback times are probably most realistic, but at the same time vary strongly depending on the counterfactual assumed. Unfortunately, there is no perfect feedstock type in terms of carbon. Thinnings may be most optimal, but require further investigation. What is fortunate, is that the temporal perspective on when reference carbon stocks are determined, does not seem to matter for carbon parity payback times, allowing for a clearer discussion alternatives among parties with different views on this matter. To improve the climate mitigation effect of using wood pellets from the US South-East to provide Dutch power, the next should be to get an even better understanding of what exact (mix of) counterfactuals is relevant for a feedstock. Using this information, feedstock selection could be optimised for climate benefits – within the boundaries posed by costs of feedstock and technical possibility to process different feedstocks at the various pellet mills in the US South-East.

Acknowledgements

First of all, I would like to thank my supervisors dr. Floor van der Hilst and Anna Duden very much for their help during this project. Floor, thank you for the kind encouragements and the firm advice that I know will prove useful beyond this project as well. Anna, thank you for always taking the time for me, the constructive and fun conversations we had on this project, and of course the great company on my trip to the US.

Furthermore, I would like to say a big word of thanks to all the people that I have discussed my project with in the US and in the Netherlands, and everyone that responded to my survey questions. Your contributions have been invaluable. I would like to specifically thank: Virginia Dale for hosting me at Oak Ridge National Laboratory and taking time and effort to show me and Anna around; Keith Kline for co-hosting and his useful and honest feedback; Adam Taylor for sharing his extensive experience and showing us around the saw mill; Gregg Marland for a very useful talk, a fantastic day in Boone and the answers to the many follow-up questions that I had; Mike Jostrom, Bob Emory, Ben Wigley, Reid Miner, Bob Abt and Barry Parrish for their extensive answers and the discussions on my survey questions; Maggie Davis and Anne Freels, for making me feel right at home in Tennessee; and back in the Netherlands: Gert-Jan Jonker for our useful talks and Martin Juninger for (second-)reading this encyclopaedia.

Lastly, I would like to thank the people close to me for their wonderful support during my research.

References

Abt, K. L., Abt, R. C., & Galik, C. (2012). Effect of Bioenergy Demands and Supply Response on Markets, Carbon, and Land Use. *Forest Science*, *58*(5), 523–539.

Abt, K. L., Abt, R. C., Galik, C. S., & Skog, K. E. (2014). *Effect of Policies on Pellet Production and Forests in the U . S . South*.

Agostini, A., Giuntoli, J., & Boulamanti, A. (2013). *Carbon accounting of forest bioenergy* (p. 88).

Bernier, P., & Paré, D. (2013). Using ecosystem CO2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy*, *5*, 67–72.

Biobasedeconomy.nl (2015). *Discussie over inzet biomassa voor bio-energie: een reconstructie.* [Online] Available at*:* http://www.biobasedeconomy.nl/2015/01/29/discussie-over-inzet-biomassa-voor-bio-energie-een-reconstructie/ [accessed March 18, 2015].

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., & Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *Forest Ecology and Management*, *289*, 501–514.

Buchholz, T., & Gunn, J. (2015). *Carbon Emission Estimates for Drax biomass powerplants in the UK sourcing from Enviva Pellet Mills in U . S . Southeastern Hardwoods using the BEAC model*.

Buchholz, T., Hurteau, M., Gunn, J., & Saah, D. (2015). A global meta-analysis of forest bioenergy greenhouse gas emissions accounting studies. *GCB Bioenergy*, 1-9.Burkhart, H. E., Farrar, K. D., Amateis, R. L., & Daniels, R. F. (2001). *Simulation of Individual Tree Growth and Stand Development in Loblolly Pine Plantations on Cutover , Site-Prepared Areas* (p. 33).

CBS (2014). Hernieuwbare energie in Nederland 2013. Centraal Bureau voor de Statistiek. Den Haag/Heerlen.

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S. (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*, *53*, 434–447.

Cherubini, F., Bright, R. M., & Strømman, A. H. (2012). Site-specific global warming potentials of biogenic CO 2 for bioenergy: contributions from carbon fluxes and albedo dynamics. *Environmental Research Letters*, *7*, 045902.

Cherubini, F., Strømman, A. H., & Hertwich, E. (2011a). Effects of boreal forest management practices on the climate impact of CO2 emissions from bioenergy. *Ecological Modelling*, *223*(1), 59–66.

Cherubini, F., Peters, G. P., Berntsen, T., Strømman, A. H., & Hertwich, E. (2011b). CO_2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. *GCB Bioenergy*, *3*, 413–426.

Chiang, J. M., McEwan, R. W., Yaussy, D. a., & Brown, K. J. (2008). The effects of prescribed fire and silvicultural thinning on the aboveground carbon stocks and net primary production of overstory trees in an oak-hickory ecosystem in southern Ohio. *Forest Ecology and Management*, *255*(5-6), 1584–1594.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., … Pingoud, K. (2011). Bioenergy. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, … C. von Stechow (Eds.), *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Colnes, A., Doshi, K., Emick, H., Evans, A., Perschel, R., Robards, T., … Sherman, A. (2012). *Biomass Supply and Carbon Accounting for Southeastern Forests* (p. 132).

Comas, L. H., & Eissenstat, D. M. (2004). Linking fine root traits to maximum potential growth rate among 11 mature temperate tree species. *Functional Ecology*, *18*(3), 388–397.

Deckmyn, G., Muys, B., Garcia Quijano, J., & Ceulemans, R. (2004). Carbon sequestration following afforestation of agricultural soils: Comparing oak/beech forest to short-rotation poplar coppice combining a process and a carbon accounting model. *Global Change Biology*, *10*(9), 1482–1491.

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science*, *30*(2), 219–230.

Dwivedi, P., Bailis, R., Bush, T. G., & Marinescu, M. (2011). Quantifying GWI of Wood Pellet Production in the Southern United States and Its Subsequent Utilization for Electricity Production in The Netherlands/Florida. *Bioenergy Research*, *4*, 180–192.

Dwivedi, P., Khanna, M., Bailis, R., & Ghilardi, A. (2014). Potential greenhouse gas benefits of transatlantic wood pellet trade. *Environmental Research Letters*, *9*, 24007.

ECN (2007). *Notitie: Vragen over nieuwe kolencentrales in Nederland; aan: Ministerie van Economische Zaken*. Energy research Centre of the Netherlands.

ECN (2015). Online database. *ECN Phyllis II database on biomass*. Energy research Centre of the Netherlands. [Online] available at: https://www.ecn.nl/phyllis2/ [accessed July 29, 2015].

EEA (2005). *Characterization of the US Commercial/Industrial Boiler Population*. Energy and Evironmental Analysis Inc. Arlington.

EPA (2014). *Emission factors for Greenhouse Gas Inventories.* US Environmental Protection Agency. available at: *www.epa.gov/climateleadership/documents/emission-factors.pdf*

EPA (2006). Solid Waste Management and Greenhouse Gases. US Environmental Protection Agency [Online; latest update March 2015; older version used by Ingerson, 2010] available at: http://epa.gov/epawaste/conserve/tools/warm/SWMGHGreport.html [accessed July 30, 2015].

Essent (2015). Amercentrale. [Online] available at:https://www.essent.nl/content/overessent/het_bedrijf/opwekking/amercentrale/index.html [accessed July 29, 2015].

European Parliament and EU Council, Directive 2009/28/EC (23 April 2009) on the Promotion of the Use of Energy from Renewable Sources. *Official Journal of the European Union,* L 140 (EN), 16–62.

Eurostat (2015). Share of renewable energy in gross final energy consumption. [Online] Available at:

http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=t2020_31 [accessed March 18, 2015].

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(February), 1235–1238.

Fox, T. R., Jokela, E. J., & Allen, H. L. (2007). The Development of Pine Plantation Silviculture in the Southern United States. *Journal of Forestry*, (October/November), 337–347.

Gibbs, H. K., Johnston, M., Foley, J. a, Holloway, T., Monfreda, C., Ramankutty, N., & Zaks, D. (2008). Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters*, *3*, 1-10.

Galik, C. S., & Abt, R. C. (2015). Sustainability guidelines and forest market response: an assessment of European Union pellet demand in the southeastern United States. *GCB Bioenergy*, 1–12.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., & Kellomäki, S. (2007a). Changed thinning regimes may increase carbon stock under climate change: A case study from a Finnish boreal forest. *Climatic Change*, *81*(3-4), 431–454.

Garcia-Gonzalo, J., Peltola, H., Zubizarreta Gerendiain, A., & Kellomäki, S. (2007b). Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. *Forest Ecology and Management*, *241*(1-3), 243–257.

García-Quijano, J. F., Deckmyn, G., Ceulemans, R., Van Orshoven, J., & Muys, B. (2008). Scaling from stand to landscape scale of climate change mitigation by afforestation and forest management: A modeling approach. *Climatic Change*, *86*(3-4), 397–424.

Goh, C. S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., … Deutmeyer, M. (2012). Wood pellet market and trade: a global perspective. *Biofuels, Bioproducts and Biorefining*, *7*, 24–42.

Gonzalez-Benecke, C. a., Martin, T. a., Cropper, W. P., & Bracho, R. (2010). Forest management effects on in situ and ex situ slash pine forest carbon balance. *Forest Ecology and Management*, *260*(5), 795–805.

Gonzalez-Benecke, C. a., Martin, T. a., Jokela, E. J., & De La Torre, R. (2011). A flexible hybrid model of life cycle carbon balance for loblolly pine (Pinus taeda L.) management systems. *Forests*, *2*(3), 749–776.

Guest, G., Cherubini, F., & Strømman, A. H. (2013). Climate impact potential of utilizing forest residues for bioenergy in Norway. *Mitigation and Adaptation Strategies for Global Change*, *18*(8), 1089–1108.

Harmon, M.E. (2012) The Forest Sector Carbon Calculator. [Online] Available at: http://landcarb.forestry.oregonstate.edu/default.aspx [accessed March 18, 2015].

Heath, L. S., Nichols, M. C., Smith, J. E., & Mills, J. R. (2010a). *FORCARB2: an updated version of the U. S. forest carbon budget model*.

Holtsmark, B. (2010). *Use of wood fuels from boreal forests will create a biofuel carbon debt with a long payback time* (p. 34).

Holtsmark, B. (2012a). The outcome is in the assumptions: Analyzing the effects on atmospheric CO2 levels of increased use of bioenergy from forest biomass. *GCB Bioenergy*, *5*, 467–473.

Holtsmark, B. (2012b). Harvesting in boreal forests and the biofuel carbon debt. *Climatic Change*, *112*, 415–428.

Hoover, C., & Stout, S. (2007). The carbon consequences of thinning techniques: Stand structure makes a difference. *Journal of Forestry*, *105*(5), 266–270.

Horner, G. J., Baker, P. J., Mac Nally, R., Cunningham, S. C., Thomson, J. R., & Hamilton, F. (2010). Forest structure, habitat and carbon benefits from thinning floodplain forests: Managing early stand density makes a difference. *Forest Ecology and Management*, *259*(3), 286–293.

Ingerson, A. (2011). Carbon storage potential of harvested wood: Summary and policy implications. *Mitigation and Adaptation Strategies for Global Change*, *16*(3), 307–323.

IPCC (2013). Anthropogenic and Natural Radiative Forcing, Chapter 8. In: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. a. (2004). *Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species*.

Jiménez, E., Vega, J. a., Fernández, C., & Fonturbel, T. (2011). Is pre-commercial thinning compatible with carbon sequestration? A case study in a maritime pine stand in northwestern Spain. *Forestry*, *84*(2), 149–157.

Johnson, T. G., Bentley, J. W., & Howell, M. (2011). *The South ' s Timber Industry — An Assessment of Timber Product Output and Use , 2009*.

Jonker, J. G. G., Junginger, M., & Faaij, A. (2013). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, 1–19.

Keyser, T. L., & Zarnach, S. J. (2012). Thinning, age, and site quality influence live tree carbon stocks in upland hardwood forests of the southern Appalachians. *Forest Science*, *58*(5), 407–418.

Kittler, B., Price, W., McDow, W., & Larson, B. (2012). *An Evaluation of Forestry Programs to Meet European Biomass Supply Chain Requirements*

KNAW (2015). *Report on the Symposium 'Biofuel And Wood As Energy Sources', 10 April 2015, KNAW, The Trippenhuis, Amsterdam*. Amsterdam, KNAW.

Kull, S. J., Rampley, G. J., Morken, S., Metsaranta, J., Neilson, E. T., & Kurz, W. A. (2011). *Operational-Scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) user's guide* (p. 344).

Kurz, W. A., Apps, M. J., Webb, T. M., & McNamee, P. J. (1992). *The carbon budget of the Canadian forest sector: phase I* (p. 93).

Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw, C. H., Rampley, G. J., … Apps, M. J. (2009). CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling*, *220*, 480–504.

Lamers, P., Junginger, M., Hamelinck, C., & Faaij, A. (2012). Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. *Renewable and Sustainable Energy Reviews*, *16*(5), 3176–3199.

Lamers, P., & Junginger, M. (2013a). The “debt” is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels, Bioproducts and Biorefining*, *7*, 373–385.

Lamers, P., Thiffault, E., Paré, D., & Junginger, M. (2013b). Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass and Bioenergy*, *55*, 212–226.

Lamers, P., Hoefnagels, R., Junginger, M., Hamelinck, C., & Faaij, A. (2014a). Global solid biomass trade for energy by 2020: An assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. *GCB Bioenergy*, 1–17.

Lamers, P., Junginger, M., Dymond, C. C., & Faaij, A. (2014b). Damaged forests provide an opportunity to mitigate climate change. *GCB Bioenergy*, *6*, 44–60.

Landsberg, J. J., & Waring, R. H. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency , carbon balance and partitioning. *Forest Ecology and Management*, *95*, 209–228.

Lindgren, P. M. F., & Sullivan, T. P. (2013). Long-term responses of tree and stand growth of young lodgepole pine to pre-commercial thinning and repeated fertilization. *Forest Ecology and Management*, *307*, 155–164.

van Loo, S. & Koppejan, J. eds. (2008). *Handbook of Biomass Combustion and Co-Firing*; Twente University Press. Twente.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., … Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature*, *455*(September), 213–215.

Magelli, F., Boucher, K., Bi, H. T., Melin, S., & Bonoli, A. (2009). An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy*, *33*(3), 434–441.

Marland, G., & Schlamadinger, B. (1997). Forests for carbon sequestration of fossil fuel substitutition? A sensitivity analysis. *Biomass and Bioenergy*, *13*(6), 389–397.

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology*, *45*(2), 789–795.

Miner, R. A., Abt, R. C., Bowyer, J. L., Buford, M. A., Malmsheimer, R. W., Laughlin, J. O., … Skog, K. E. (2014). Forest Carbon Accounting Considerations in US Bioenergy Policy. *Journal of Forestry*, *112*, 591–606.

Mitchell, S. R., Harmon, M. E., & O’Connell, K. E. B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, *4*, 818–827.

Mund, M., Kummetz, E., Hein, M., Bauer, G. ., & Schulze, E.-D. (2002). Growth and carbon stocks of a spruce forest chronosequence in central Europe. *Forest Ecology and Management*, *171*(3), 275–296.

New York Times (2015). *A Biofuel Debate: Will Cutting Trees Cut Carbon?* February 10, 2015 [Online] Available at: http://www.nytimes.com/2015/02/11/business/economy/a-biofuel-debate-will-cutting-trees-cut-carbon.html?_r=0 [accessed March 18, 2015].

Noormets, A., Mcnulty, S. G., Domec, J. C., Gavazzi, M., Sun, G., & King, J. S. (2012). The role of harvest residue in rotation cycle carbon balance in loblolly pine plantations. Respiration partitioning approach. *Global Change Biology*, *18*(10), 3186–3201.

NRDC (2015). *Think Wood Pellets are Green? Think Again.*

Pinchot Institute for Conversation. (2013). *The Transatlantic Trade in Wood for Energy: A Dialogue on Sustainability Standards and Greenhouse Gas Emissions*. Savannah, Georgia, USA.

Plantinga, A. J., & Birdsey, R. A. (1993). Carbon fluxes resulting from U.S. private timberland management. *Climatic Change*, 37–53.

Pohjola, J., & Valsta, L. (2007). Carbon credits and management of Scots pine and Norway spruce stands in Finland. *Forest Policy and Economics*, *9*(7), 789–798.

Powers, M. D., Kolka, R. K., Bradford, J. B., Palik, B. J., Fraver, S., & Jurgensen, M. F. (2012). Carbon stocks across a chronosequence of thinned and unmanaged red pine (Pinus resinosa) stands. *Ecological Applications*, *22*(4), 1297–1307.

Prestemon, J. P., Wear, D. N., & Foster, M. O. (2015). *The Global Position of the U . S . Forest Products Industry*.

Repo, A., Känkänen, R., Tuovinen, J. P., Antikainen, R., Tuomi, M., Vanhala, P., & Liski, J. (2011). Forest bioenergy climate impact can be improved by allocating forest residue removal. *GCB Bioenergy*, *4*, 202–212.

Repo, A., Tuomi, M., & Liski, J. (2010). Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy*, *3*, 107–115.

Richards, F.J. (1959). A flexible growth function for empirical use. *Journal of experimental botany*. 10, 290-300.

Russell, M. B., Woodall, C. W., Fraver, S., D’Amato, A. W., Domke, G. M., & Skog, K. E. (2014). Residence Times and Decay Rates of Downed Woody Debris Biomass/Carbon in Eastern US Forests. *Ecosystems*, *17*(5), 765–777.

RVO (2015). *Brandstoffenlijst t.b.v. Tier2 methode EU ETS-bedrijven rapportage over 2014.* Rijksdienst Voor Ondernemend Nederland [Netherlands Enterprise Agency]. Utrecht.

Saunders, M., Tobin, B., Black, K., Gioria, M., Nieuwenhuis, M., & Osborne, B. a. (2012). Thinning effects on the net ecosystem carbon exchange of a Sitka spruce forest are temperature-dependent. *Agricultural and Forest Meteorology*, *157*, 1–10.

Schlamadinger, B., Canella, L., Marland, G. & Spitzer, J. (1997). Bioenergy strategies and the global carbon cycle. *Scientific Geological Bulletin*, 50, 157–182.

Schlamadinger, B., & Marland, G. (1996a). Full fuel cycle carbon balances of bioenergy and forestry options. *Energy Conversion and Management*, *37*(95), 813–818.

Schlamadinger, B., & Marland, G. (1996b). The role of forest and bioenergy stragies in the global carbon cycle. *Biomass and Bioenergy*, *10*(95), 275–300.

Searates.com (2015). International Container Shipping Platform. [Online] available at: searates.com [accessed July 29, 2015].

Searchinger, T. D. (2010). Biofuels and the need for additional carbon. *Environmental Research Letters*, *5*(2), 1–10.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., … Tilman, G. D. (2009). Fixing a Critical Climate Accounting Error. *Science*, *326*(October), 527–528.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., … Yu, T.-H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, *319*, 1238–1240.

Sikkema, R., Junginger, M., Pichler, W., Hayes, S., & Faaij, A. P. C. (2010). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, *4*, 132–153.

Sikkema, R., Steiner, M., Junginger, M., Hiegl, W., Hansen, M. T., & Faaij, A. (2011). The European wood pellet markets: current status and prospects for 2020. *Biofuels, Bioproducts and Biorefining*, *5*, 250–278.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States*.

Smith, W. B., Miles, P.D., Perry, C.H. & Pugh, S.A. (2007). *Forest Resources of the United States, 2007. Technical document supporting the Forest Service 2010 RPA Assessment.*

Spelter, H., & Toth, D. (2009). *North America ' s Wood Pellet Sector*.

SOMO (2013). *From Whence the Wood?* Stichting Onderzoek Multinationale Ondernemingen [Centre for Research on Multinational Corporations]. Amsterdam.

Stephenson, A. L., & MacKay, D. J. (2014). *Life Cycle Impacts of Biomass Electricity in 2020* (p. 154).

Sullivan, B. W., Kolb, T. E., Hart, S. C., Kaye, J. P., Dore, S., & Montes-Helu, M. (2008). Thinning reduces soil carbon dioxide but not methane flux from southwestern USA ponderosa pine forests. *Forest Ecology and Management*, *255*(12), 4047–4055.

Thiffault, E., Endres, J., McCubbins, J. S. N., Junginger, M., Lorente, M., Fritsche, U., & Iriarte, L. (2015). Sustainability of forest bioenergy feedstock supply chains: local, national and international policy perspectives. *Biofuels, Bioproducts and Biorefining*, *9*, 283–292.

Tsoularis, A. (2001). Analysis of logistic growth models. *Research Letters in the Information and Mathematical Sciences*, *2*, 23–46.

US Forest Service (2015). Forest Vegetation Simulator. [Online] Available at: http://www.fs.fed.us/fmsc/fvs/ [accessed March 18, 2015].

US Forest Service RPA (2010). *Future of America's Forests and Rangelands, 2010 Resources Planning Act Assessment.* Washington D.C.

Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, B., … Saah, D. (2010). *Biomass Sustainability and Carbon Policy Study*.

WDNR (2010). *Forest Biomass and Air Emissions*. Washington Department of Natural Resources. Olympia.

Wear, D., & Greis, J. (2012). *Summary Report The Southern Forest Futures Project* (p. 54).

Wear, D.N. & Greis, J.G. (2013). The Southern Forest Futures Project: technical report. Available at: http://www.srs.fs.usda.gov/pubs/44183 [accessed March 18, 2015].

Wear, D.N. & Greis, J.G. (2013). The Southern Forest Futures Project: technical report. Available at: http://www.srs.fs.usda.gov/pubs/44183 [accessed March 18, 2015].

Zanchi, G., Pena, N., & Bird, N. (2010). *The upfront carbon debt of bioenergy*. *Joanneaum Research* (p. 56). Graz.

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*, 761–772.

Annex I

Table 8 (below) gives an overview of carbon debt and parity payback times of wood pellets used to produce bioenergy found in recent studies, along with the most important characteristics of each study.

Table 8. *Overview of carbon debt and parity payback times of wood pellets used to produce bioenergy found in recent literature, including the most important characteristics of each study. Studies are grouped per biome. Where multiple payback times are given (separated by commas) all the study's characteristics are kept the same except for the category displayed in red font. Descriptions of (counterfactual) scenarios, abbreviations and notes (indicated by superscript numbers) are given below the table.*

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]	efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
boreal													
Bernier & Paré, 2013 (Saskatchewan and Quebec, Canada)	jack pine and black spruce, resp.	CEM	-	120	-	harvest: stem	LCA	local	oil th.	-	**-**	protection	**90**
Holtsmark, 2010 (Norway)	Norwegian spruce	RTP	-	90	FL	add. harvest: stem	no	local	coal el.	internal	-	BAU2	**150**
Holtsmark, 2012b (Norway)	Norwegian spruce	RTP	-	90	FL	add. harvest: stem	no	local	coal el.	internal	-	BAU3	**190**

Table 1 continued

Author (study area)	**tree type**	**forest data**	**management intensity or [productivity]**	**rotation period (years)**	**methodological approach**	**scenario and bioenergy feedstock[6]**	**efficiency of value chain (partially) included, if yes via:**	**transatlantic transport/local use**	**fossil system replaced**	**model**	**carbon debt payback time (years)**	**Counterfactual scenario**	**carbon parity payback time (years)**
sub-boreal													
Lamers et al. 2014b (British Columbia, Canada)	pine only pine-dominated spruce-dominated spruce-fir	RTP	-	60	SL	BAU 1	LCA	trans-atlantic	coal el.	CBM-CFS3	**20, 25, 37, 39**	protection	**0, 0, 37, 54**
					SL	1st harvest					**30, 37, 47, 47**	protection	**16, 30, 46, 51**
					SL	1st harvest					**30, 37, 47, 47**	BAU1	**92, 92, 92, 88**
					SL +FL[5]	Slash scenario					**0, 10 , 26, 30**	BAU1	**0, 0, 0, 0**
					SL + FL	Protection[7]					**142, 82, 52, 0**	-	**-**
					FL	BAU 1					**54, 47, 42, 8**	protection	**0, 0, 32, 61**
					FL	1st harvest					**56, 62, 75, 61**	protection	**0, 22, 73, 84**
					FL	1st harvest					**56, 62, 75, 61**	BAU1	**53,94,109,103**

Table 1 continued

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]	efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
northern temperate/alpine													
Zanchi et al., 2012 (Austria)	Norwegian spruce	RTP	low	90	FL	add. harvest[8]: stem	no	local	coal el.	GORCAM	-	BAU4	**175**
									gas el.		-		**300**
			high	90		add. harvest[9]: stem			coal el.		-		**230**
									gas el.		-		**400**
			low	90		harvest residues			coal el.		-		**0**
									oil el.		-		**7**
									gas el.		-		**16**
			low	irr.		plantation on margin. land; whole tree			any		**0**[10]	marginal land	**0**
			[high]	10		harvest residues			coal el.		**17**[10]	protection	**17**
									oil el.		**20**[10]		**20**
									gas el.		**25**[10]		**25**
			[low]	20		harvest residues			coal el.		**114**[10]		**114**
									oil el.		**145**[10]		**145**
									gas el.		**197**[10]		**197**

Table 1 continued

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]	efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
northern temperate													
McKechnie et al., 2011 (Ontario, Canada)	regional mix of soft- and hard wood	FI (GE)	-	60-100	DL	harvest residues add. harvest: stem	LCA	local	coal el.	FORCARB-ON	- -	BAU5	**16** **38**
Mitchell et al., 2012 (US pacific North-West)	Parameterisation range based on regional forests	RTP	[0.35, 0.54, 0.84 $\Delta C_{stem}/\Delta C_{leaf}$] for 25, 50 and 100 year rotation period resp.	25 - 100	FL	post-agricultural forest; harvest: 50% or 100% of stems	BCE	local	US el.	LANDCARB	**~1**	protection (or enable regrowth)	**~50 to >1000 where carbon parity times are shortest for old growth, followed by disturbed, rotational and post-agricultural forests**
				25 50 100		rotation forest,; harvest: 100% of stems					**~100 to >1000** **~1 to 900** **~1**		
				25 - 100		rotation forest; harvest 50% of stems					**~1**		
						recently disturbed forest; harvest: 50% or 100% of stems					**20 to 1000**		
						old growth forest; harvest: 50% or 100% of stems					**19 to 1000**		

Table 1 continued

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]		efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
northern temperate (continued)														
Walker et al., 2010 (US North-East)	regional mix of pine and hardwoods	RTP[2]	-	SH ~90[4]	SL	existing forests; % aboveground biomass harvested:	38%	LCA	local	oil th. coal el. gas th. gas el.	USFSVS	-	heavy BAU	**3, 12, 17, 45**
							60%						heavy BAU	**7, 21, 24, >90**
							76%						heavy BAU	**14, 30, 36, 89**
							38%						light BAU	**15, 25, 28, 86**
							60%						light BAU	**10, 27, 31, 59**
							76%						light BAU	**15, 32, 37, 85**

Table 1 continued

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]		efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
southern temperate														
Marland & Schlamadinger, 1997 (US South-East)	NS	RTP	[1.72 tC ha^{-1} yr^{-1}]	30	SL + FL	marginal land conv. to forest; harvest: 80% of aboveground biomass;20% res. left		BCE	local	coal el.	GORCAM	0	protection (of planted forest)	~100[11]
Colnes et al., 2012 (US South-East)	regional mix (GE)	FI (GE)[1]	-	35	DL	additional harvest: whole tree		LCA	90% trans-atlantic	various	USFSVS + others (p. 76 report)	-	BAU5	35-50
Jonker et al., 2013 (US South-East)	southern softwoods (pred. Loblolly shortleaf pine & longleaf slash pine)	RTP	low	25,	SL	harvest: whole tree from managed plantations (all cases); biomass (co-)firing plant efficiency (η)=	η=41%	LCA	trans-atlantic	coal el.	GORCAM	11,7,5	-	-
			med	25,	ISL		η=41%			coal el.		18,13,12	protection	39,22,17
			high	20	FL		η=41%			coal el.		1,1,1		46,27,12
							η=35%			coal el.		1,1,1		57,37,17
							η=46%			coal el.		1,1,1		39,21,8
							η=41%			EU el.		1,1,1		80,55,28
							η=41%			coal el.		1,1,1	natural regrowth	30,3,3
							η=35%			coal el.		1,1,1		46,7,4
							η=46%			coal el.		1,1,1		6,2,2
							η=41%			EU el.		1,1,1		72,41,9

Table 1 continued

Author (study area)	tree type	forest data	management intensity or [productivity]	rotation period (years)	methodological approach	scenario and bioenergy feedstock[6]	efficiency of value chain (partially) included, if yes via:	transatlantic transport/local use	fossil system replaced	model	carbon debt payback time (years)	Counterfactual scenario	carbon parity payback time (years)
non-specified biome													
Schlamadinger & Marland, 1996a (NS)	NS	RTP	[2 tC ha-1 yr-1	60	SL	harvest: 55% traditional uses, 22% bioenergy, 23% residue left	BCE	local	US el.	GORCAM	~40	-	-
			[6 tC ha-1 yr-1][3]	7		former agri. land conv. to plantation; harvest: 80% bioenergy, 20%					0	-	-

Abbreviations: NS = not specified; GE = geospatially explicit; CEM = combined empirical CO2 measurements (see Bernier & Paré, 2013); RTP = representative theoretical plots (see Lamers et al., 2013a); FI (GE) = forest inventory (geospatially explicit); SH = single harvest, plot is only harvested once so rotation period irrelevant; irr. = irrelevant; SL = stand level (see Jonker et al., 2013); ISL = increasing stand level (see Jonker et al., 2013); FL = fixed landscape (see Lamers et al., 2013a); DL = dynamic landscape (see Lamers et al., 2013a); BAU = business as usual; res. = harvest residues; add. = additional; LCA = life cycle analysis (accounting for value chain efficiency by determining all carbon emissions in the value chain); BCE = biomass conversion efficiency (including value chain efficiency via some conversion factor η from harvested biomass to the pellets that replaces fossil fuels, may not include the full life cycle); el. = electric (i.e. used for electricity generation); th. = thermal (i.e. used for heating and cooling); EU el. = average European fossil fuel mix used for electricity generation; US el. = average United States fossil fuel mix used for electricity generation; gas = natural gas only; USFSVS = United States Forest Service Vegetation Simulator. **Scenarios descriptions:** additional harvest means in addition to traditional uses; BAU1 = BAU harvest for traditional uses only, including salvage logging of dead trees, burn harvest residues (to reduce fores fire fuel loads), use sawdust for pellet production; BAU2 = BAU with low harvesting levels, slightly declining biomass in old forest; BAU3 = BAU with low harvesting levels, constant biomass in old forest; BAU4 = BAU harvest for traditional uses only (60% of aboveground biomass per harvest); BAU5 = BAU harvest for traditional uses only; heavy BAU heavy = BAU harvesting 32% of aboveground biomass for traditional use (timber); light BAU = BAU harvesting 20% of aboveground biomass for traditional use (timber); Slash = non-merchantable trees, merchantable tree slash and sawdust are all used for pellets; 1st harvest for pellets = dedicated salvage logging of dead trees in severely damaged forests and use wood for pellet production, subsequent harvests follow the slash scenario; protection = leave the forest unharvested and unmanaged; natural regrowth = the tree plantation is harvested once, then left unmanaged and unharvested. **Notes**: [1]Forest inventory based on the US Forest Inventory Analysis (FIA); [2]Representative theoretical plots based on US Forest Inventory Analysis (FIA), carbon debt defined as additional emissions of burning biomass as compared to fossil fuels (Walker et al., 2010); [3]Initial growth rate, declines afterwards; [4]A rotation period of 90 years would be suitable according the authors; [5]carbon parity payback times were based on the stand level approach; [6]if not indicated otherwise (e.g. whole tree used) harvest residues are left to decompose; [7]leaving damaged forests unharvested will also cause a net release of carbon in the short- and medium term; [8]An increase in harvests from 60% to 80% of aboveground biomass; [9]An increase in harvest from 60% to 80% of the annual increment of aboveground biomass; [10]The carbon stock of the counterfactual was assumed to be constant, hence carbon debt payback times are equal here to the calculated carbon parity payback times; [11]carbon parity payback time was estimated from graphs presented in the article.

Annex II

The carbon payback time studies that were analysed in annex I used four different carbon accounting (or carbon budget) models and one vegetation simulator (US forest service, 2015). These four models are described below. Lastly, the LCA-style BEAC model (Stephenson & MacKay, 2014) is discussed, which forms an alternative to carbon accounting models for calculating carbon payback times.

LANDCARB (Harmon, 2012) is a forest carbon accounting model that simulates an ecosystem at the landscape-level using a grid of cells representing stands (Mitchell et al., 2012). It follows carbon through 7 live pools, 1 mortality pool and 3 stable carbon pools and at the same time allows to compilation of fossil carbon offsets. Vegetation growth is climate-driven, and growth, mortality and decomposition dynamics are species specific and also depend on intra and inter-specific competition (Mitchell et al., 2012). LANDCARB was made for the state of Oregon specifically; the most recent version is LANDCARB 3.0, of which only a simplified forest sector carbon calculator is publicly available (Harmon, 2012)..

The CBM-CFS3 model is a carbon budget model (equivalent to carbon accounting model) developed for the Canadian forestry sector (Kull et al., 2011). Its earliest precursor was described by Kurz et al. (1992); CBM-CFS3 version 1.2 is the most recent update (Kull et al., 2011). The model can assess carbon stocks and their changes due to forest management and natural disturbances both at the landscape and stand-level (Kurz et al., 2009; Kull et al., 2011). CBM-CFS3 can work at a large geographic scale and use multiple forest inventories as input data (Kurz et al., 2009). Growth is based on empirical yield curves (Kurz et al., 2009). The model consists of several live and dead carbon pools (Kurz et al., 2009; Kull et al., 2011). Carbon dynamics (including growth) are modelled within and between these pools. Carbon accounting (of CO_2, CO and CH_4) is based on transfers between these pools: live pools extract carbon from atmosphere through growth, then natural disturbances, biomass turnover and litterfall, and human disturbances (including harvesting) transfer carbon to the dead pools, from which carbon is released to the atmosphere via decay (Kurz et al., 2009). Lamers et al. (2014b) used CBM-CFS3 to calculate carbon payback times (see annex I).

FORCARB is a forest carbon budget model developed by Plantinga & Birdsey (1993) to estimate carbon stores of US forests; it was part of broader set of models used to assess timber resources. The most recent version is FORCARB2 (Heath et al., 2010a). FORCARB2 is a landscape-level model. It models several above- and belowground carbon pools (Heath et al., 2010a). The model consists of equations to estimate the current (or future) carbon stocks of these pools based on (expected) forest inventory data and as such includes both forested area and carbon per area (Heath et al., 2010a). Growth rates are based on yield curves which are again based on forest inventory data (Heath et al., 2010a). FORCARB2 only includes the carbon stores in the forest (Heath et al., 2010a), what happens with carbon after harvesting is only modelled to a limit extent; its system boundaries are narrower compared to the other carbon accounting models presented in this section. McKechnie et al. (2011) used an adaptation of FORCARB for Ontario to calculate carbon payback times of wood pellets.

The Graz/Oak Ridge Carbon Accounting Model (GORCAM) developed by Schlamadinger & Marland (1996b) is a spreadsheet based model that determines the carbon balance of forest or agricultural land. It models the accumulation of carbon in various carbon pools and the flows between them (Schlamadinger & Marland, 1996b). These pools include: aboveground vegetation pools, belowground carbon pools, forest product pools (e.g. timber and paper), fossil emission offsets of bioenergy, and even the fossil fuels not used because wood-based products are used instead (e.g. using wood instead of steel in construction; Schlamadinger & Marland, 1996b). It is possible to model different forest management regimes by adjusting parameterisation (Schlamadinger & Marland, 1996b). Growth is modelled with a simple logistic growth function (Schlamadinger & Marland, 1996b; Jonker et al., 2013). GORCAM was used by Schlamadinger & Marland (1996a), Marland & Schlamadinger (1997), Zanchi et al. (2012) and Jonker et al. (2013) to calculate carbon payback times.

The model can be adjusted to a specific region and has been used to model the US South-East (Jonker et al., 2013; Marland & Schlamadinger, 1997).

A recently developed LCA-style model (used by Stephenson & MacKay, 2014) forms an alternative to carbon accounting models to help calculate carbon payback times. This Bioenergy Emissions And Counterfactual (BEAC) model determines the GHG emissions of various bioenergy types, including wood pellets, along their entire value chain, using a large data set of emissions associated with the various steps (Stephenson & MacKay, 2014). Different from previous life cycle analyses of the carbon balance of wood pellets (e.g. Magelli et al., 2009; Sikkema et al., 2010; Cherubini et al., 2014), this model considers the carbon debt of bioenergy and enables the calculation of carbon debt payback times (Stephenson & MacKay, 2014). Moreover it allows the comparison of a scenario with a counterfactual scenario (Stephenson & MacKay, 2014) and therefore the calculation of carbon parity payback times.

Annex III

The knowledge and experience shared by various forest and wood pellet stakeholders and experts, the majority of which from the US South-East formed an important input to this study. The author spent time in the US South-East, speaking to many experts and after returning to the Netherlands, various email/Skype conversations were held to further increase the author's understanding of wood pellet (feedstock) production and the associated carbon dynamics. Furthermore, a survey was held on wood pellet feedstock types and counterfactual scenarios. This annex gives an overview of the survey questions and respondents, and lists the experts that were contacted beyond this survey.

Survey questions

The survey questions asked were essentially the same for all experts and stakeholders, except that the first question was phrased differently, depending on the respondents' perspective (see below) and that pellet mills were also asked about shipping to the EU and the Netherlands. Questions asked were (per type of respondent):

Pellet mills

1) Are you able to provide me with information on the specific types and relative shares/amounts of feedstock (in-wood residues, sawdust, different types of hardwood/softwood roundwood, etc. etc.) that are used to produce wood pellets at the plant?
2) I am also trying to get an idea of what would have happened with the wood pellet feedstock had there not been a wood pellet demand and had the feedstock not been used for wood pellets. What do you think would have happened to different feedstock types had there not been a wood pellet demand (e.g. used in different industries, left as residues, not harvested at all, etc.)?
3) Do you export pellets to Europe? And specifically, the Netherlands?

Corporate foresters

1) Are you able to provide me with information on the types and relative shares/amounts of feedstock (in-wood residues, different types of roundwood, etc.) that [corporate forester] delivers to wood pellet mills?
2) I am also trying to get an idea of what would have happened with the wood pellet feedstock had there not been a wood pellet demand and had the feedstock not been used for wood pellets. What do you think would have happened to different feedstock types had there not been a wood pellet demand (e.g. used in different industries, left as residues, not harvested at all, etc.)?

Other experts

1) What specific feedstock types are used for wood pellet production in the US South-East (in-wood residues, sawdust, different types of hardwood/softwood roundwood, etc. etc.), and do you have any information of their relatives shares in production?
2) What do you think would have happened to different feedstock types had there not been a wood pellet demand and had the feedstock not been used for wood pellet production, i.e. what do you think are correct counterfactuals for the different feedstock types? (used in different industries, left as residues, not harvested at all, etc.)?

Survey respondents

Table 9 (below) gives an overview of the respondents to the survey questions that are outlined in the previous subsection.

Table 9. *Overview of survey respondents and their affiliations.*

respondent	affiliation	notes
Mike Jostrom	Plum Creek (large corporate forester)	
Bob Emory	Weyerhaeuser (large corporate forester)	
Ben Wigley	National Council for Air and Stream Improvement (NCASI)	NCASI performs natural resources research for the forest products industry
Reid Miner	National Council for Air and Stream Improvement (NCASI)	
Bob Abt	North Carolina State University	
Dennis Hazel	North Carolina State University	
Keith Kline	Oak Ridge National Laboratory	(survey questions asked via Skype)
Virginia Dale	Oak Ridge National Laboratory	(survey questions asked via Skype)
Adam Taylor	University of Tennessee	
Adam Macon	Dogwood Alliance (regional environmental NGO)	campaigns against wood pellets production
Kim Cesafsky	Enviva Amory Plant (pellet mill)	
	Enviva Wiggins Plant (pellet mill)	
	Enviva Ahoskie Plant (pellet mill)	
	Enviva Northampton Plant (pellet mill)	
	Enviva Cottondale Plant (pellet mill)	
	Enviva Pellets Southhampton, LLC (pellet mill)	
Barry Parrish	Georgia Biomass LLC (pellet mill)	
Alison Hunt	BTH Quitman Hickory LLC torrefaction facility (pellet mill)	was not able to provide information
Matt O’Malley	O’Malley wood pellets (pellet mill)	
Claire Brant	Equustock Virginia Plant (pellet mill)	
Joey Summer	Woodlands Alternative Fuels (pellet mill)	

People conacted on wood pellets (beyond survey)

Many forest and wood pellet experts were contacted beyond the survey (the majority while the author was in the US South-East), and on various specific topics (wood pellet feedstock types and availability, forests, forest product market dynamics, carbon dynamics of forests, soils, wood pellets, etc.). An overview of these people is given in table 10. Where specific information provided by one of these experts was used in this thesis, the expert is included in the references list (via personal communicationl; see references).

Table 10. *Overview of forest and wood pellet experts spoken with beyond the survey*

expert	affiliation	notes
Virginia Dale	Oak Ridge National Laboratory	
Keith Kline	Oak Ridge National Laboratory	
Mac Post	Oak Ridge National Laboratory (formerly)	
Kevin Hoyt	University of Tennessee Arboretum	
Adam Taylor	University of Tennessee	
Tim Young	University of Tennessee	
Neelam Poudyal	University of Tennessee	
Don Hodges	University of Tennessee	
John Coulston	North Carolina State University / USDA	only attended his talk
Gregg Marland	Appalachian State University	
Eric Marland	Appalachian State University	
Laurel Bates	Appalachian State University	
Bob Emory	Weyerhaeuser (large corporate forester)	
Ben Wigley	National Council for Air and Stream Improvement (NCASI)	NCASI performs natural resources research for the forest products industry
Gert-Jan Jonker	Utrecht University	
Martin Junginger	Utrecht University	
Anna Duden	Utrecht University	beyond supervising, discussing her experiences while in the US

Annex IV

This annex provides background tables and figures for the results section.

Table 11. *Default, minimum and maximum carbon debt payback times.*

feedstock category	**tree type**	**default** (years)	**minimum** (years)	**maximum** (years)
low-quality roundwood	softwood	15	3	29
	hardwood	21	3	42
harvest residues	softwood	16	8	28
	hardwood	22	10	40
mill residues	softwood	16	8	28
	hardwood	22	10	40

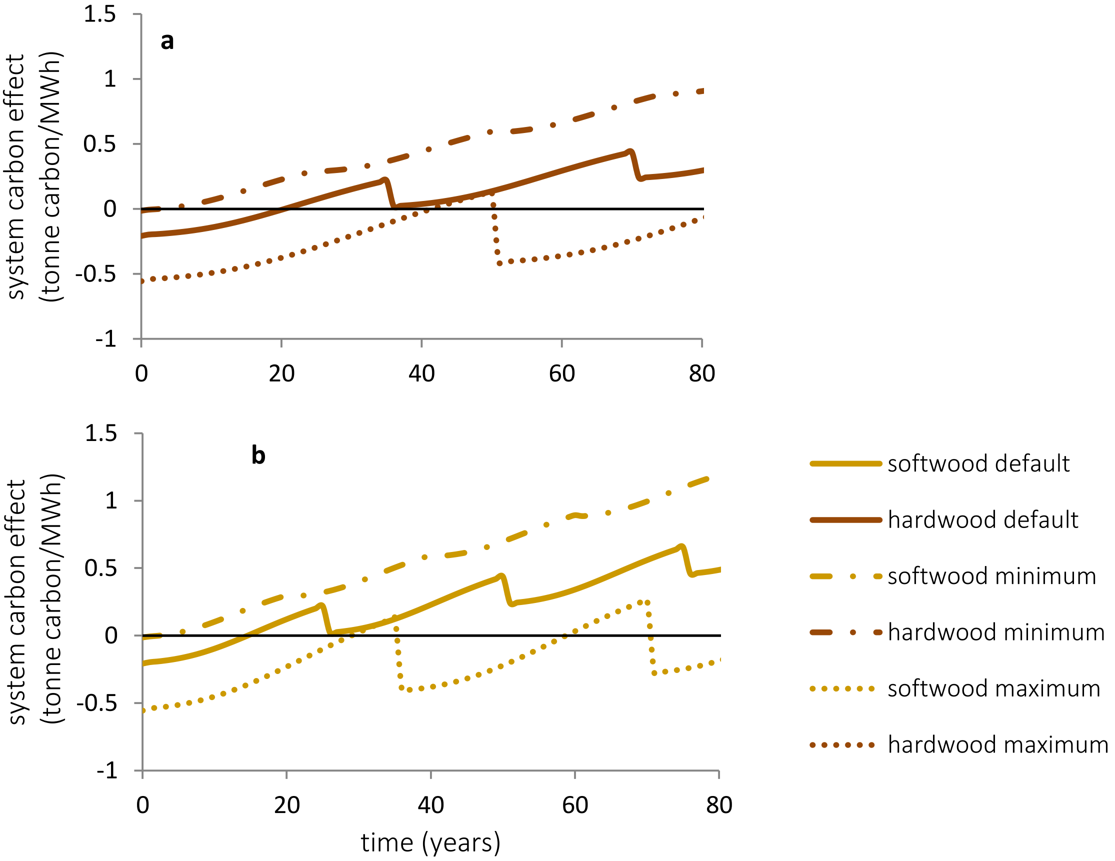


Figure 15. *Carbon balances of wood pellets from low-quality roundwood used for bioelectricity: default parameterisations and parameterisations (within parameter ranges found in this study) that yield minimum and maximum carbon debt payback times.*

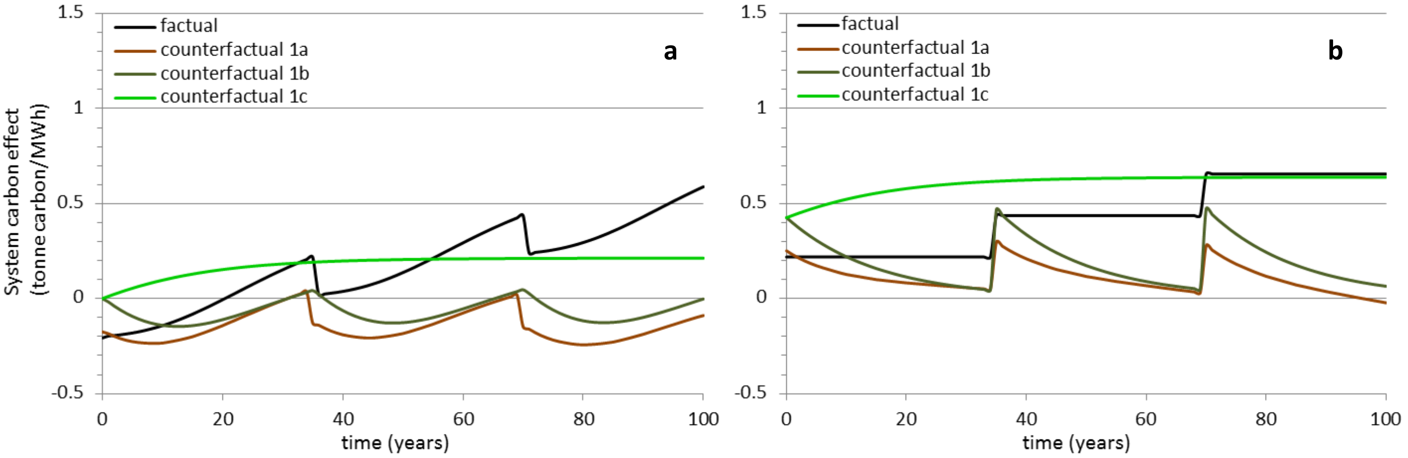
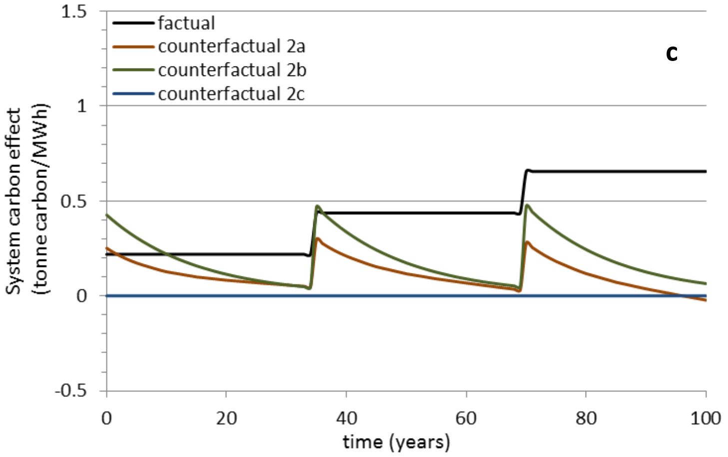


Figure 16. *Carbon balances of wood pellets used for bioelectricity production from hardwood feedstocks (factuals) and their counterfactual. Figures:* ***a)*** *and* ***b)*** *low-quality roundwood 1st and 2nd temporal perspective respectively;* ***c)*** *thinnings;* ***d)*** *and* ***e)*** *harvest residues 1st and 2nd temporal perspective, respectively;* ***f)*** *and* ***g)*** *mill residues 1st and 2nd temporal perspectives, respectively. For descriptions of counterfactuals see section 2.5.*



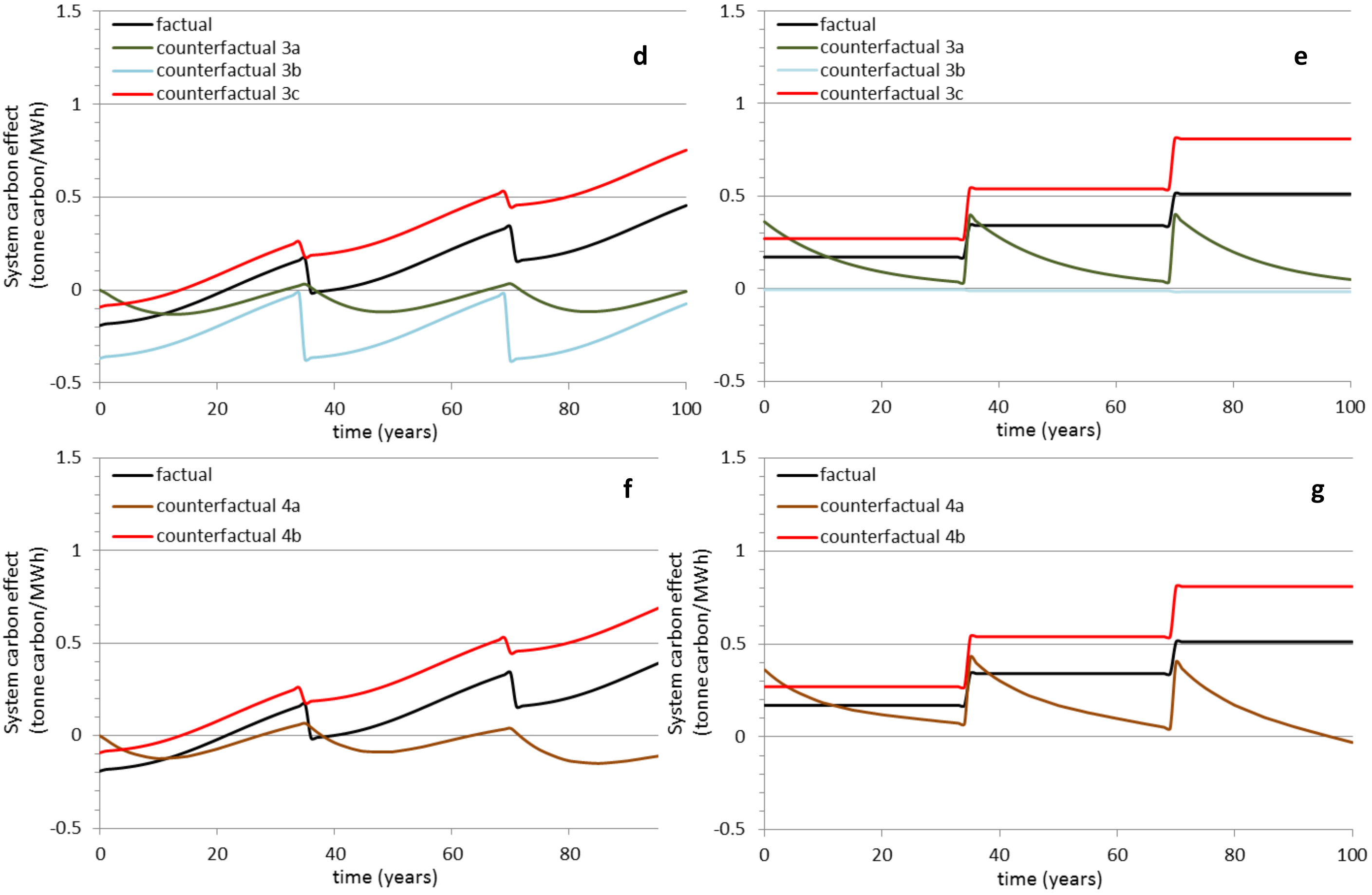


Table 12. *Default, minimum and maximum carbon parity payback times.*

feedstock category	counter-factual	tree type	first temporal perspective			second temporal perspective		
			default (years)	minimum (years)	maximum (years)	default (years)	minimum (years)	maximum (years)
low-quality roundwood	1a	softwood	1	0	*26*	1	0	*39*
		hardwood	2	0	*50*	2	0	>100
	1b	softwood	*20*	2	>100	*20*	2	>100
		hardwood	*11*	1	44	*11*	1	*44*
	1c	softwood	*24*	8	>100	50	20	>100
		hardwood	*33*	9	>100	70	25	>100
thinnings	2a	softwood	-	-	-	1	0	*39*
		hardwood	-	-	-	2	0	>100
	2b	softwood	-	-	-	*20*	2	>100
		hardwood	-	-	-	*11*	1	*44*
	2c	softwood	-	-	-	0	0	0
		hardwood	-	-	-	0	0	0
harvest residues	3a	softwood	*21*	6	99	*21*	6	*99*
		hardwood	*11*	3	*24*	*11*	3	*24*
	3b	softwood	0	0	0	0	0	0
		hardwood	0	0	0	0	0	0
	3c	softwood	never	never	never	never	never	never
		hardwood	never	never	never	never	never	never
mill residues	4a	softwood	*10*	3	never	*10*	3	never
		hardwood	*12*	3	never	*12*	3	never
	4b	softwood	never	never	never	never	never	never
		hardwood	never	never	never	never	never	never

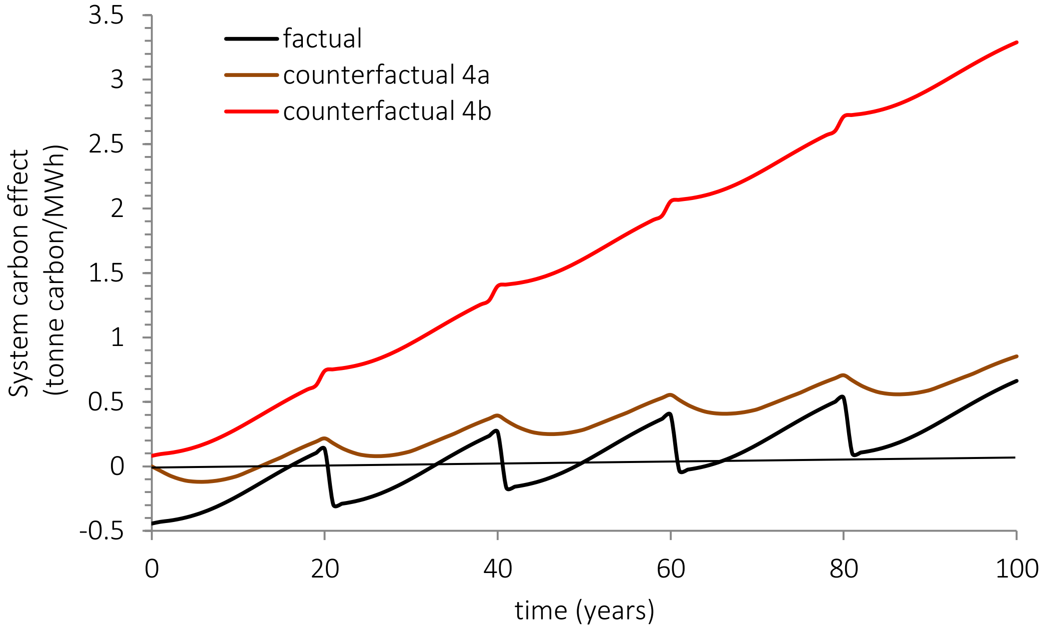


Figure 17. *Assuming parameterisation for "maximum carbon parity payback time": The carbon balance of wood pellet from softwood mill residues softwood assuming the first temporal perspective, compared to counterfactuals 4a (mill residues used to produce forest products) and 4b (mill residues used to provide heat locally, replacing fossil fuels).*