# The Green Choice

## Biomass use for a sustainable future

Swinda Pfau

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Floodplain of Bemmel, The Netherlands (S .Pfau)

# Chapter 1

## General introduction

## 1.1 Introduction

The extensive use of fossil fuels and materials is one of the biggest challenges today: it is largely responsible for human-induced climate change with all its negative consequences and causes air and water pollution as well as land degradation. Since the industrial revolution, modern societies depend on fossil fuels for a great variety of applications. With our current consumption patterns, it is hardly imaginable to forego the luxury of constantly creating and consuming new products. Would it not be great, if we had an alternative for fossil resources to fulfil our desire for new goods and more energy; if we could produce products in a better way, without the negative consequences? This is the promise of a bioeconomy: a way out of fossil resource consumption, while continuing the provision of commodities in a more sustainable way. But many scientific controversies and societal debates cast doubts on the validity of this promise, and in recent years it has become apparent that the bioeconomy is not a silver bullet. Many choices influence whether biomass use contributes to a sustainable future.

### 1.1.1 The upcoming bioeconomy

The basic idea of a bioeconomy is to switch from a fossil economy, using fossil resources for the production of energy (including fuels) and materials, to an economy based on biomass, making it more sustainable by reducing greenhouse gas (GHG) emissions and avoiding other negative consequences of fossil resource extraction and consumption. Initially, conceptions of the bioeconomy were focusing on bioenergy. Bioenergy refers to energy or energy carriers (e.g. fuels and gas) produced from biomass, which can be produced using various technologies, including for example combustion, gasification, or anaerobic digestion. Bioenergy is considered a renewable energy source and the focus on bioenergy is linked to the important position that renewable energy production occupies in climate mitigation efforts. Later, attention extended to so-called bio-based products, including for example biochemicals, bioplastics or insulation materials. Bio-based products are material applications, where biomass replaces fossil resources in the production process. The growing attention for the bioeconomy, bioenergy and bio-based products in scientific discourse can be deduced from the number of scientific publications covering one or more of these focus areas, as shown in Figure 1.1.

The transition to a bioeconomy has not only received attention in scientific discourse, but also in policy making. Several countries as well as the European Union have developed strategies for the development of a bioeconomy [1–6]. It is appraised as a system with the potential to bridge economic interests and sustainability in various sectors (e.g. energy, food, chemistry). In policy documents, several arguments in favour of a transition towards a bioeconomy are given: contribution to climate change mitigation, increased sustainability, energy security, self-sufficiency (and independence from other countries or regions) and economic opportunities, especially in rural areas [1,7–10].

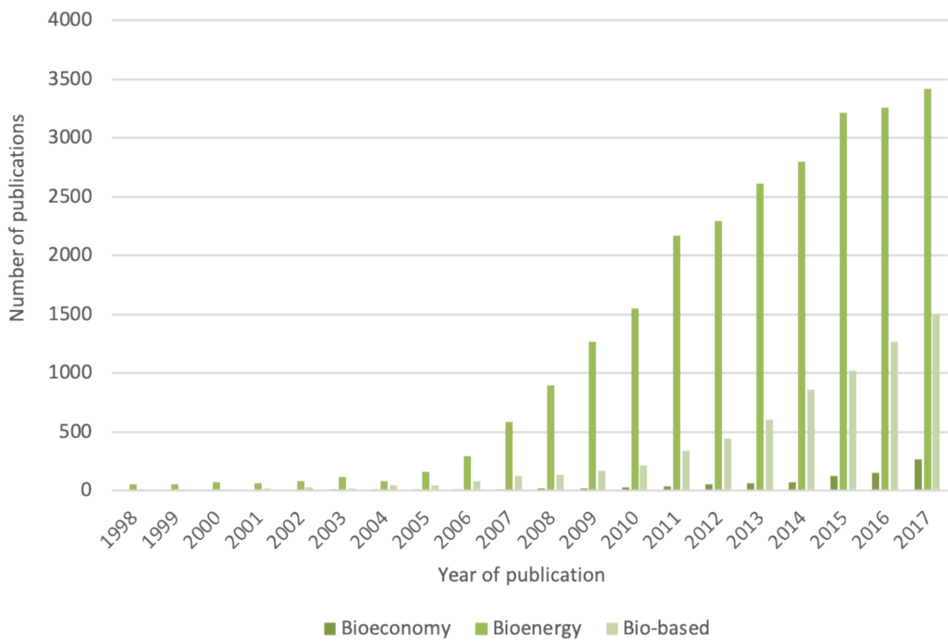


Figure 1.1 Number of publications including the terms bioeconomy ("bioeconomy", bio-economy", bio-based economy"), bioenergy ("bioenergy", "bio-energy", "bio energy", "biofuel", "bio-fuel") or bio-based ("biobased", "bio-based", "bio based") in title, abstract or keywords per year of publication. Based on Web of Science database search (May 10, 2018).

#### 1.1.2 Sustainability of the bioeconomy

While many scientists as well as policy makers expect a positive contribution of the bioeconomy to sustainability, various controversies in scientific and public debates suggest that some doubts may be in order as to whether a transition towards a bioeconomy will necessarily lead to a better, more sustainable situation [8,9,11,12]. Best known is the 'food versus fuel' debate, where mainly the use of edible crops for fuel production is criticised. But also the general assumption that a bioeconomy is a sustainable alternative to our current use of fossil resources is questioned.

In scientific literature, discussions revolve around the GHG balance of bioenergy. Bioenergy is generally considered a renewable energy source, because it features a short carbon cycle in contrast to fossil resources. Plants sequester $CO_2$ from the atmosphere during photosynthesis, building organic material. The same carbon atoms are subsequently released during bioenergy production and can be taken up again by plants. This cycle can be repeated in a short timescale, which makes the process renewable and in principle carbon flux neutral. When bioenergy is used to replace fossil fuels, which release carbon that has been stored for a very long time, a significant reduction of GHG emissions can be achieved [13]. Criticism of the argumentation that bioenergy is carbon neutral mainly revolves around, on the one hand, the origin and production of biomass and, on the other hand, the assumption that carbon neutral means climate neutral.

To provide biomass for bioenergy production on a large scale, biomass has to be produced specifically for this purpose (referred to as cultivated, purpose-grown or dedicated biomass production). Typically, biomass is supplied from forestry or agricultural production. In both cases, important drawbacks of biomass for energy production are discussed in the literature, which challenge the assumed carbon neutrality of bioenergy. Biomass production requires fossil fuel input (e.g. fertilisers, use of agricultural or harvesting machinery, transport and processing (e.g. refining)). The emissions caused by biomass production have to be subtracted from the GHGs saved due to replacement of fossil energy. Additionally, one of the most important aspects discussed is the use of land. When land is used to cultivate biomass for energy, it cannot at the same time be used for other purposes, such as food production, or be conserved as a natural area. If more biomass is to be produced on a global scale, this will cause either direct or indirect land-use change [12,14–16]. Land-use change (LUC) can be defined as any change of one type of land-use to another [15]. This occurs either directly, when natural land is converted specifically for the purpose of growing biomass for energy production, or indirectly (iLUC), when land formerly used for biomass production for other purposes, for example food, is used for biomass for energy production and natural land elsewhere on the globe is consequently converted to make up for the lost production area. Both direct and indirect LUC can cause significant GHG emissions, that counteract the GHG emissions saved during the replacement of fossil energy [14,15,17]. As a consequence, bioenergy production is usually not carbon neutral, due to the emissions during biomass production and land-use emissions. Depending on the specific situation, it can still be beneficial in terms of GHG emissions in comparison to the fossil resources it replaces. But the more emissions are caused by biomass production, the longer it takes before it pays off. This effect is called the carbon (or GHG) payback time; i.e. the time it takes before GHG emissions caused by biomass production are offset by GHG savings achieved through the replacement of fossil energy. Carbon payback times can vary significantly based on the situation [18–22]. A proposed alternative for biomass production is the cultivation of aquatic biomass, mainly algae, in seawater or on marginal land unfit for traditional agriculture, thus avoiding competition for land areas. Cultivation and processing techniques have been under development for years and are currently further advanced, aiming for example at the production of biofuels [23–25], but land-based biomass production is dominant.

In another line of reasoning it is argued that even if bioenergy were carbon neutral, it may not necessarily be climate neutral. Climate change is caused by the radiative force of increasing amounts of GHGs in the atmosphere. The longer GHGs remain in the atmosphere, the more they contribute to climate change. When biomass is harvested and applied for bioenergy, $CO_2$ is released, causing a so-called carbon debt [26]. The same carbon can subsequently be absorbed again by replanted biomass. The time between the initial emission and the reabsorption determines the contribution to climate change, because this is the period in which $CO_2$ resides in the atmosphere [27]. This is referred to as the rotation time of biomass production, which may be short (e.g. one year for bioenergy crops that are harvested and replanted each year) or long (e.g. 50 years for forest biomass, where trees are harvested after longer growth periods). Especially for forest biomass, this biogenic emission of carbon and its effect in the atmosphere is argued to be essential in the analysis of the GHG balance of bioenergy [27]. While the scientific discourse regarding the GHG balance is focussed on bioenergy, these issues are not necessarily restricted to bioenergy. Bio-based products may face similar challenges if cultivated biomass is used, although the dimensions may differ due to longer periods before carbon is released after the use of products. Sometimes the usefulness of the application of biomass for either energy or bio-based products is debated. Bioenergy is heavily criticised as being inefficient in reducing GHG emissions. Moreover, it is argued that fossil resources as raw material for the production of bio-based products, for example bioplastics, can currently only be replaced by biomass, while there are alternative, more efficient sources of renewable energy (such as photovoltaic and wind energy) [28,29]. Contrastingly, it is argued that using biomass for bioenergy production is more urgent in efforts to mitigate climate change. Bioenergy is currently the biggest renewable energy source world wide [30].

Finally, other factors besides GHG emissions are also important for the overall sustainability of the bioeconomy. Sustainability is not just about GHG emissions, but also includes other environmental, economic and social dimensions. Creutzig et al. [17] provide an extensive overview of potential implications of the bioeconomy for these other dimensions. Examples for other environmental impacts are negative impacts on terrestrial and aquatic ecosystems and biodiversity, caused by deforestation, agricultural intensification and LUC, but also positive impacts if degraded land is occupied. Social impacts may include a reduction of food security, caused by competing land-uses, but also local employment opportunities, especially in rural areas. Economic impact might be a concentration of incomes and increased poverty, but the use of waste and residues is argued to create socio-economic benefits [17].

### 1.1.3 Residual biomass

The drawbacks of cultivating biomass for the bioeconomy have triggered attention for residual biomass as a resource. Residual biomass is not produced specifically for the market, but is a by-product from other, primary activities. These primary activities can be dedicated biomass cultivation, for food or biomass production, but also other activities that result in biomass residues, which are then considered a by- or waste product. Residual biomass includes harvesting and processing residues from agriculture (e.g. the fibrous, non-productive parts of crops, rice husks or sugarcane bagasse) and forestry (e.g. tree tops and branches, logging or sawmill residues), biogenic waste streams from industrial production (e.g. potato skins or animal fats), animal manure, post-consumer wastes (e.g. demolition wood, organic waste and sewage sludge) and landscape residues (e.g. biomass released during management of roadside vegetation and natural areas) [17,31–33].

Residual biomass is now discussed as one of the second-generation resources for bioenergy and bio-based products [34–36]. It is suggested as a strategy to avoid the negative effects associated with land-use change. Residual biomass resources are associated with lower sustainability risks, in particular due to lower land and water use. New technologies are expected to enable the use of residues that would otherwise be waste as input for new production chains, increasing the overall efficiency of resource use. Cultivated biomass, which is generally of a higher quality, may then be reserved for other purposes, such as food production. However, residual biomass is seldom without function, which may be lost if resources are redirected to new applications [36–38].

## 1.2 Goals and outline of this study

Against the background of this debate about the pros, cons and limitations of the bioeconomy, the dissertation project documented in this book had two main objectives. The first one was to investigate the relationship between sustainability and bioeconomy and more specifically the role of biogas in bioeconomy policies. The second one was to investigate the conditions under which the use of residual biomass contributes to sustainability.

The sustainability of biomass use is approached from different angles. This includes a broad review of sustainability issues of the bioeconomy and a closer look at specific strategies to contribute to sustainability through the use of biomass. Part I of this thesis deals with general issues with regard to the bioeconomy, while Part II has a specific focus on residual biomass. An overview of the chapters is shown in Figure 1.2 and the goals of each chapter are presented in Table 1.1.

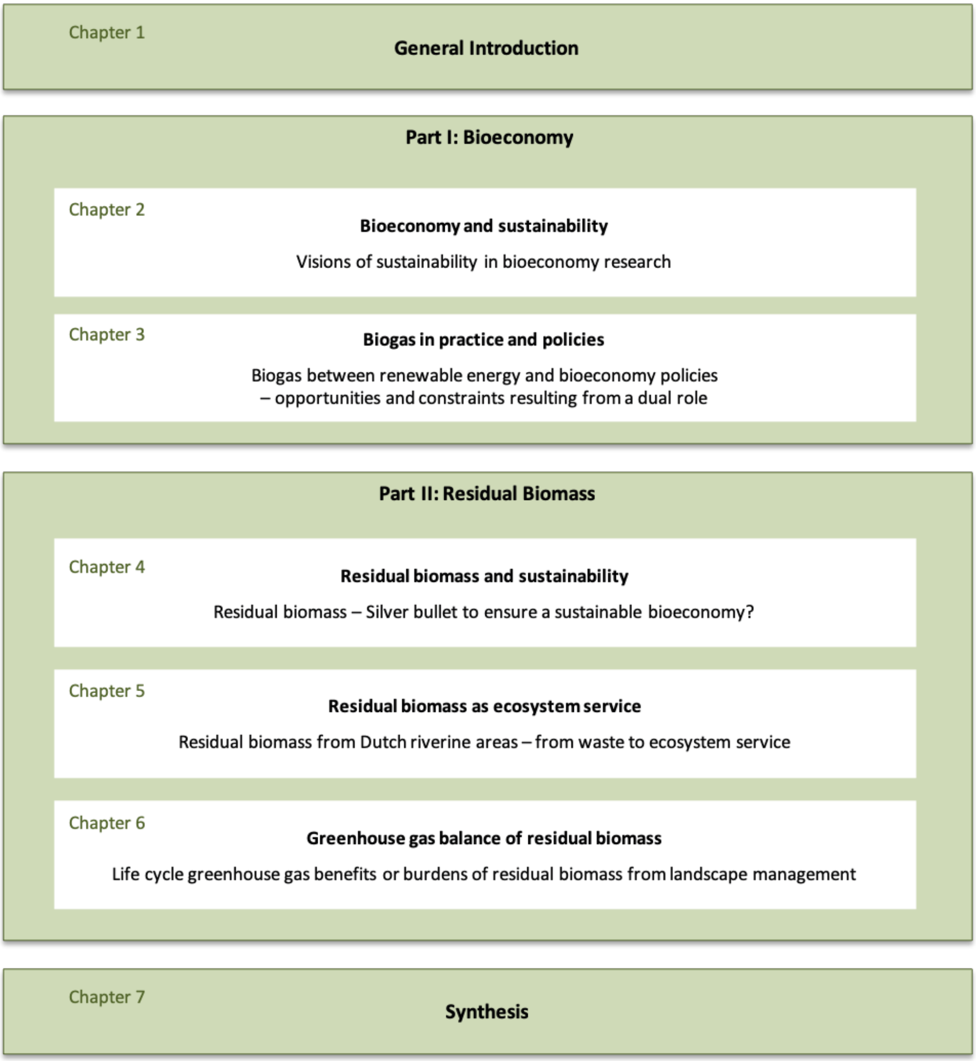


Figure 1.2 Chapter overview.

Part I starts with a broad exploration of the scientific discourse concerning the sustainability of the bioeconomy, presented in Chapter 2. Chapter 3 provides an in-depth assessment of the current practice of an important biomass application, biogas. Biogas plays an important role in bioeconomy policies, but also in the renewable energy policy domain, resulting in a competition over scarce biomass resources between policy domains. This overlap presented an interesting case to analyse how the efficiency and sustainability of biomass use could be maximised.

Table 1.1 Goals of each chapter.

| Part | Chapter | Goal |
|---|---|---|
| I | Chapter 2 | Give a systematic overview of the way sustainability is addressed in the scientific literature about the bioeconomy. |
| | Chapter 3 | Examine the relationship of current biogas practice with the bioeconomy and renewable energy policy domains and identify how biogas can contribute to both. |
| II | Chapter 4 | Discuss conditions that determine whether use of residual biomass contributes to sustainability. |
| | Chapter 5 | Explore the transition from waste to ecosystem service of residual biomass in Dutch water management organisations, including current uses of biomass, drivers for these uses and organisation of vegetation management and biomass use. |
| | Chapter 6 | Quantify the net GHG emissions of various options to apply residual biomass released during landscape management in riverine areas. |

Communication with stakeholders as reported in Chapter 3 revealed a growing interest for the valorisation of residual biomass. The focus of the second part of this project as reported in Part II has therefore been narrowed down to residual biomass in general and then to residual biomass from landscape management. Chapter 4 broadly explores the sustainability promises and implications of residual biomass use. As described in Section 1.1.3, residual biomass is a by- or waste product, but it is not necessarily without function, which leads to the question under which conditions residual biomass use for new applications contributes to sustainability. The two subsequent chapters focus on the case of residual biomass released during landscape management in riverine areas. Public stakeholders engaged in vegetation management in these areas are very interested in the potential to use residual biomass to contribute to sustainability while at the same time reducing management costs. This engagement by stakeholders is an interesting case because it mirrors scientific attention for residual biomass in practice and provided an opportunity to study the practical implications of residual biomass use. First, the organisational implications and the consideration of sustainability of residual biomass use in current practice were studied. The results are presented in Chapter 5. This revealed a lack of quantitative evaluation criteria for the sustainability of biomass use, which is addressed through a comparison of GHG emissions of various current applications of residual biomass from riverine landscapes in Chapter 6.

## 1.3 Methodology

In view of the great variety of drivers, sectors and sustainability issues involved, the development of the bioeconomy is considered a multi-disciplinary subject. It is therefore only natural that it has been approached from the perspective of various scientific disciplines. Past and current research efforts focus on biological and biotechnological aspects (e.g. comparison and improvement of feedstocks, biological treatment and processing [39,40]), technology (e.g. technologies to valorise biomass, comparison of efficiencies [41–43]), economical aspects (e.g. economic impacts of extending biomass use, impacts on other markets [44–46]), social impacts (e.g. impacts on availability and prices of food or employment opportunities [47,48]) and environmental aspects (e.g. life cycle analyses of supply chains, environmental impacts of extending biomass use [17,49]).

Moreover, the bioeconomy involves a great variety of societal actors. This includes companies, but also public organisations in various roles, for example as legislators, policy makers, land owners or biomass owners. These societal actors influence for a large part how the bioeconomy is shaped. Creating a sustainable bioeconomy is a complex societal challenge. Societal challenges, and especially problems related to sustainability, are argued to require the involvement of not only academic knowledge, but also of practical, experiential knowledge of the societal actors or stakeholders involved [50–52]. This calls for transdisciplinary approaches, where researchers and societal stakeholders are involved from the beginning, contributing and integrating different types of knowledge and expertise [50–53]. In multi-disciplinary research, a certain issue is addressed by more than one discipline and in interdisciplinary research, multiple disciplines address a certain issue together, sharing knowledge and striving for joint knowledge production. In transdisciplinary settings, scientific knowledge from multiple disciplines is integrated with input from societal stakeholders for joint knowledge production [54]. The main goal of transdisciplinary research addressing complex challenges is societal impact [52,53].

This thesis approaches the sustainability of biomass use from different angles, involving different methods and integrating practical knowledge of various stakeholders. The goals and research questions of the empirical chapters were developed based on a combination of scientific and practical relevance, established from personal communication with stakeholders. They furthermore make use of the knowledge of societal actors in different ways.

Table 1.2 Types of data collected and methods applied in each chapter.

| Part | Chapter | Type of data | Method |
|---|---|---|---|
| I | Chapter 2: Visions of sustainability in bioeconomy research | Theoretical | Systematic literature review |
| | Chapter 3: Biogas between renewable energy and bioeconomy policies | Empirical; qualitative | Stakeholder interviews |
| II | Chapter 4: Residual biomass: silver bullet to ensure a sustainable bioeconomy? | Theoretical | Literature review |
| | Chapter 5: Residual biomass from Dutch riverine areas – from waste to ecosystem service | Empirical; qualitative | Stakeholder interviews |
| | Chapter 6: Life cycle greenhouse gas benefits and burdens of residual biomass from landscape management | Empirical; quantitative | Greenhouse gas emission calculation |

Table 1.2 shows the type of data and the methods applied for each chapter. The different goals of the chapters (shown in Table 1.1) called for different methods. Chapter 2 and 4 are theoretical explorations of broader issues, and are therefore based on scientific literature. In Chapter 2, a systematic review was chosen to be able to present a comprehensive overview of views on sustainability in bioeconomy research at the time. Chapter 4 is focussed on a specific strand of literature, addressing the sustainability of residual biomass use. The remaining chapters are based on empirical data, addressing or integrating societal stakeholders' knowledge. Chapters 3 and 5 are based on case studies, using stakeholder interviews to gather insights on current practice. As is appropriate in qualitative research, purposefully selected participants were chosen that would best help understand the problem and research question [55]. Semi-structured interviews were chosen to ensure that the same topics were addressed in each interview, but at the same time allowing for individual conversations, where opinions and experiences of participants could be addressed. Chapter 6 is based on a

quantitative study, typically addressing a closed-ended question with predetermined, unbiased approaches and numeric data [55].

## 1.4 Making a green choice

Making a 'green choice' might be to choose biomass over fossil resources for the production of energy and materials in a bioeconomy. But more choices need to be made, as there are different biomass resources to choose from and various applications of each biomass resource. These choices all determine if and how much biomass use contributes to a sustainable future. Whether or not a choice turns out to be 'green' then depends on knowledge about the physical consequences of each choice, for example in terms of emissions, but also on policies and practice influencing the playing field surrounding biomass use. In the previous sections several issues that are of importance for the sustainability of biomass use were briefly discussed. This section describes how these issues are addressed in the various chapters of this thesis.

### 1.4.1 Development of biomass use and the bioeconomy

Biomass has always been used by mankind, but in the last centuries both the amounts and applications have changed dramatically. Parts of the history of biomass supply and demand are described in Chapter 4, focussing on the relation to sustainability. More recently, the development of the bioeconomy has influenced our view on biomass, as discussed in Section 1.1.1. The basic idea that biomass is a sustainable alternative to fossil resources is only one driver to engage in a bioeconomy. Other drivers for the bioeconomy and consequences for sustainability are discussed in Chapter 2. Furthermore, Chapter 2 presents various expectations, conditions and problems regarding the sustainability of the bioeconomy, as presented in the scientific literature. Strategies for sustainable biomass use, such as cultivating biomass on marginal land, are addressed, as well.

### 1.4.2 Sustainable biomass resources

The choice of biomass resources strongly influences whether biomass use contributes to sustainability. As mentioned in Section 1.1.2, unsustainable supply of biomass is one of the biggest concerns regarding the bioeconomy. This mainly revolves around cultivation of biomass, causing emissions during production and harvest and land occupation. Depending on the landscape and type of biomass, significant emissions are a consequence of increased biomass production. Residual biomass, discussed in Section 1.1.3, is suggested as a sustainable alternative. Both the controversies around cultivated biomass and the strategy of using residual biomass are further discussed in chapters 2 and 4. Subsequently, residual biomass is the focus of Part II of this thesis and its potentials but also limitations are explored extensively in Chapters 4-6.

### 1.4.3 Biomass applications and consequences of biomass use

The choice of biomass applications influences whether biomass use contributes to sustainability. In many cases, biomass applications will replace fossil-based products and hereby achieve a positive impact. But as different biomass uses replace different products, the efficiency of the contribution to sustainability is variable. Furthermore, biomass uses have consequences beyond the replacement of conventional products. The choice of applications is often related to traditions, practical considerations and policies. This is addressed specifically in Chapters 3 and 5 but also discussed in other chapters.

As described in Secion 1.1.1, biomass can be used to produce bioenergy and bio-based products. There are many different biomass applications characterised by very different uses and functions, and historically biomass has always been an essential resource for human life, providing food, shelter, energy and materials. In the context of the bioeconomy today we distinguish between traditional and new or innovative applications. Traditional applications include for example the use of fire wood, construction materials and food production. Innovative applications include the use of biomass for new energy sources, such as biogas, and the production of materials such as bioplastics. Throughout this thesis both traditional and innovative applications will be considered. In the theoretical Chapters 2 and 4 this is based on the scientific literature we consulted. For the empirical chapters the applications considered have been chosen in communication with relevant societal stakeholders, focussing either on one specific biomass application (Chapter 3) or various applications that are realised in current practice (Chapters 5 and 6). Chapter 3 focusses on the current practice of biogas production. It relates to the choice between biomass use for bioenergy and bio-based products discussed in Section 1.1.2. Chapter 5 explores the transition of viewing residual biomass as a waste product towards valuing it as an ecosystem service and discusses various biomass applications and their drivers in current practice. Chapter 6 also addresses various residual biomass applications occurring in practice, comparing their GHG balance.

The sustainability of the bioeconomy is closely related to the efficiency of biomass use. Chapter 3 addresses the importance of considering the efficiency of biomass use and describes different concepts to achieve efficiency. It discusses how biogas can contribute to two different policy domains, maximising both efficiency and sustainability of biomass use, and gives recommendations for collaboration between policy domains to achieve greater efficiency. Chapter 4 also discusses different views on efficient biomass use, but mainly addresses the impacts of using residual biomass for various applications. Specifically, the consequences of changing the use of residues are addressed.

### 1.4.4 The meanings of sustainability

The contribution of biomass use to sustainability is one of the core issues addressed in this thesis. Chapter 2 deals with the sustainability of the bioeconomy from a broad perspective, including environmental, social and economic issues. It addresses positive expectations regarding the effect of the bioeconomy, conditions for a contribution to a sustainable society and potential problems. It touches upon various issues around the sustainability of the bioeconomy introduced in Section 1.1.2. In the following chapters, the focus shifts mainly towards environmental impacts. Environmental concerns are important drivers for the bioeconomy and are especially relevant in dealing with residual biomass, because concerns regarding the environmental impact of cultivated biomass are the main drivers for the use of residues. Chapters 4 and 6 identify various environmental aspects that should be considered when evaluating the use of biomass to contribute to a sustainable society. Chapter 6 focusses on GHG emissions, one of the most important factors determining the sustainability of biomass use.


Woody biomass, branches and crown  (S. Pfau)

# Chapter 2

## Visions of sustainability in bioeconomy research

Swinda F. Pfau, Janneke E. Hagens, Ben Dankbaar, Antoine J.M. Smits

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## Abstract

The rise of the bioeconomy is usually associated with increased sustainability. However, various controversies suggest doubts about this assumed relationship. The objective of this paper is to identify different visions and the current understanding of the relationship between the bioeconomy and sustainability in the scientific literature by means of a systematic review. After a search in several databases, 87 scientific journal articles were selected for review. Results show that visions about the relationship between bioeconomy and sustainability differ substantially. Four different visions were identified, including: (1) the assumption that sustainability is an inherent characteristic of the bioeconomy; (2) the expectation of benefits under certain conditions; (3) tentative criticism under consideration of potential pitfalls; and (4) the assumption of a negative impact of the bioeconomy on sustainability. There is considerable attention for sustainability in the scientific bioeconomy debate, and the results show that the bioeconomy cannot be considered as self-evidently sustainable. In further research and policy development, good consideration should therefore be given to the question of how the bioeconomy could contribute to a more sustainable future. Furthermore, it is stressed that the bioeconomy should be approached in a more interdisciplinary or transdisciplinary way. The consideration of sustainability may serve as a basis for such an approach.

## 2.1 Introduction

The development of the bioeconomy has recently received increasing attention, both in science and policy. In policy documents, the transition towards a bioeconomy is regularly associated with increased sustainability [1,7,56]. However, various controversies in scientific and public debates suggest doubts as to whether such a transition will necessarily lead to a better, more sustainable future. Frequently mentioned problems are the competition between food and fuel production and the negative effects of land-use change. The goal of this paper is to give a systematic overview of the way sustainability is addressed in the scientific literature about the bioeconomy.

To the best of our knowledge, no review about the scientific debate has been published to date. Some papers deal with the effects of the bioeconomy on sustainability, but mostly focus on specific elements of the bioeconomy, such as biorefineries [57–59]. Others review the role of sustainability in policy documents regarding the bioeconomy [60–62]. Altogether, they stress the importance of considering sustainability when it comes to the bioeconomy. However, none of these papers reflects on the variety of visions about sustainability in the scientific literature.

In this paper, we provide an overview of the way the relationship between sustainability and the bioeconomy is dealt with in the scientific literature. This will help to better understand the underlying visions of sustainability in bioeconomy research. Furthermore, we present an overview of the specific issues raised in the literature with regard to sustainability in the bioeconomy, providing focus points for further research and policy development. Section 2.2. describes our methodology. In Section 2.3., we present the results, first in the form of a bibliographic analysis, then distinguishing different visions on the relation between the bioeconomy and sustainability, closing with some general observations resulting from our review. We further discuss our findings in Section 2.4. with special attention for the conditions under which the bioeconomy might be sustainable. Section 2.5. concludes with some directions for future research.

## 2.2 Methodology

The approach of this paper is to systematically review the scientific literature about the bioeconomy and describe how the authors address the concept of sustainability in context with the bioeconomy. Following Fink [63] and Stechemesser et al. [64], we take a four-step approach for our literature review. The first step is the selection of research questions, databases and search terms. The second step is the application of screening criteria to identify relevant literature. The third step is the execution of the review itself, analysing the content of the selected literature based on the research question. Finally, findings are synthesised and described.

There are various definitions of the bioeconomy. Some authors consider all biotechnological advances that contribute to solving global problems as part of the bioeconomy. Others focus on either biotechnology in the life sciences or the application of biomass as a replacement of fossil materials.

In this paper, we will concentrate on the latter group of publications. The bioeconomy is generally defined in these papers as an economy in which all (or most) fossil sources used for various forms of consumption and production are replaced by biomass resources. In some policy documents and publications, the term "bio-based economy" rather than bioeconomy is used. Although it has been argued that the two are not identical [62], we have treated the terms as interchangeable for the purposes of our review, because other authors do not follow this distinction consistently.

We have not limited ourselves to specific scientific disciplines. The bioeconomy has been studied in many different disciplines from many different angles. As such, it is a typically multidisciplinary subject. In multidisciplinary research, a certain issue is addressed by more than one discipline, each following different goals and producing disciplinary knowledge. In interdisciplinary research, multiple disciplines address a certain issue together, sharing knowledge and striving for joint knowledge production. In transdisciplinary settings, scientific knowledge from multiple disciplines is integrated with input from societal stakeholders for joint knowledge production [54].

### 2.2.1 Selecting research questions, search terms and databases

To create a complete picture of how sustainability is addressed, a broad research question for the reviewing process was chosen: “How do scientific papers relate the concept of bioeconomy to sustainability?” Based on this question, two main topics were identified for this review: bioeconomy and sustainability. Since the literature about the bioeconomy was supposed to be analysed regarding their use of the sustainability concept, the bioeconomy was considered as a primary and sustainability as a secondary topic. For “bioeconomy”, various synonyms and spellings have been used as search terms: “bioeconomy”, “bio economy”, “bio-economy”, “biobased economy”, “bio based economy”, “bio-based economy”, “biomass based economy” and “biomass-based economy”. For “sustainability”, the notation, sustainab* has been used as a search term in order to also cover “sustainable” and “sustainable development”.

Because the bioeconomy is a multidisciplinary subject, we chose multiple databases in order to cover a broad range of literature that might address the bioeconomy. Five databases from the fields of natural and environmental sciences, economics and social sciences were chosen: Thomson Reuters Web of Science [65], Scirus [66], ScienceDirect [67], EconLit [68] and the International Bibliography of the Social Sciences [69].

In accordance with the choice of the bioeconomy as the primary topic and sustainability as the secondary topic, the search was conducted searching for the primary search terms in the topic (or title, keywords and abstract, depending on the database) and for the secondary search terms in the full texts or topic (in the Web of Science, full text cannot be chosen). For each search, a combination of all search terms was used, differentiating between the bioeconomy search terms with the Boolean phrase, OR, and between the bioeconomy and sustainability search terms with AND.

### 2.2.2 Application of screening criteria

Figure 2.1 shows the methods and results of the literature selection based on practical screening criteria. The database search (last conducted on 3 June 2013) resulted in 1373 hits. Since the bioeconomy concept is relatively recent, no limitations to publication dates were made. In a first refinement, the results were reduced to academic journal papers, reviews and conference proceedings in order to focus on the scientific debate about the bioeconomy. In order to give a comprehensive overview of the scientific discourse, neither limitations regarding methodology (i.e., including, for example, empirical, as well as conceptual publications), nor quality criteria (e.g., journal rankings) were made. This way, also newer journals that have not been ranked yet could be taken into account. Following this refinement, duplicates resulting from the searches in different databases were eliminated. The resulting 165 papers were screened for their relevance according to two selection questions: (1) Do the bioeconomy search terms in the document regard the use of biomass (our focus)? (2) Does the paper make a substantive connection between the two central concepts? Since databases do not cover all publications, it was decided to include additional literature, provided that it fulfilled the screening criteria. These papers were selected from previously identified literature and from screening the reference lists of the publications found in the database search.

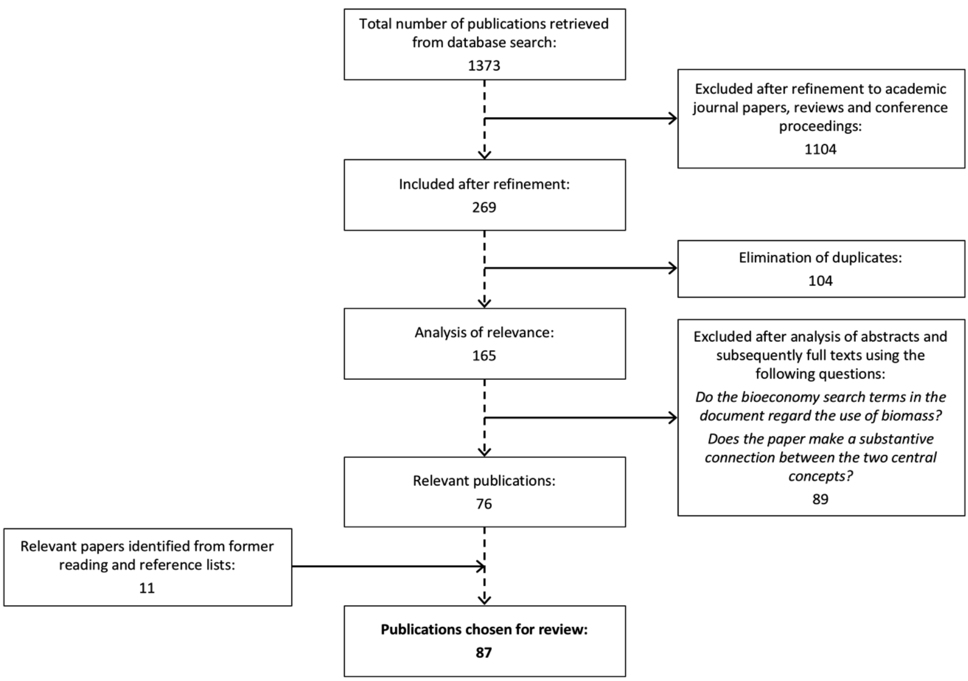


Figure 2.1 The methods and results of the literature selection.

This resulted in an additional 11 papers. In total, 87 publications were selected for review. While these publications are assumed to represent a significant proportion of the relevant literature on the concepts of bioeconomy and sustainability, it is still possible that some work has not been identified. Nevertheless, we are confident that these publications provide a rather complete coverage of scientific contributions to the debate.

### 2.2.3 Reviewing process

As the first step, a bibliographic analysis was conducted. The results are presented in Section 2.3.1.

In order to display the range of topics addressed in the publications, the research domains covered in the papers were analysed. Initially, all author keywords were grouped into topics, for example representing technical aspects (e.g., processing techniques and resource production) or consequences (e.g., environmental or social impacts). For publications that do not offer author keywords important, phrases from titles and abstracts were allocated to domains accordingly. Finally, the most important research domain was determined for each publication, based on the number of keywords or phrases per domain.

For the reviewing process regarding our main research question, the qualitative data analysis (QDA) software package, ATLAS.ti (version 7 [70]), has been used to enable a systematic and consistent approach of analysing the publications. This approach proved to be useful to identify the various topics and visions related to our research question. The analysis was conducted inductively, marking relevant text passages with codes. In a later stage, the codes were combined into categories according to similar visions on the research topic. The categories and their characteristics are presented in Section 2.3.2. Furthermore, the codes provided an overview of all issues regarding the sustainability of the bioeconomy addressed in the reviewed publications. The results are presented in Sections 2.3.2 and 2.3.3.

The fourth step of the reviewing process – the synthesis of findings – is described and discussed in the following sections.

## 2.3 Results

The results of this review are presented in three subsections. First, we will show the results of the bibliographic analysis. Then, we will present the different visions on the relation between the bioeconomy and sustainability that can be found in the reviewed literature. Finally, we will provide some general observations resulting from our review. All papers selected for review are presented in alphabetical order in Table 2.1, showing the respective research domain and category, as defined in Sections 2.3.1 and 2.3.2.

Table 2.1 Publications selected for review in alphabetical order. Per article, the publishing journal, research domain and category (as defined in Sections 2.3.1 and 2.3.2) are stated.

| **Reference** | **Journal** | **Research domain** | **Category** |
|---|---|---|---|
| Alvarenga et al. [71] | Ecological Indicators | Resources | II |
| Arancibia [72] | Technology in Society | Social | IV |
| Barney et al. [73] | Biomass and Bioenergy | Resources | IV |
| Bartolini et al. [74] | Energy Policy | Policies | IV |
| Becker et al. [75] | Energy Policy | Resources | II |
| Benning et al. [76] | The Plant Journal | Resources | II |
| Bergmann et al. [77] | Renewable and Sustainable Energy Reviews | Resources | I |
| Binder et al. [78] | Energy and Environmental Science | Processing & Technology | II |
| Boehlje et al. [44] | International Food and Agribusiness Management Review | Economics | II |
| Bramsiepe et al. [79] | Chemical Engineering and Processing | Processing & Technology | II |
| Brehmer et al. [80] | Biofuels, Bioproducts and Biorefining | Resources | II |
| Brehmer et al. [81] | Biomass and Bioenergy | Resources | II |
| Bruins et al. [82] | Biofuels, Bioproducts and Biorefining | Processing & Technology | I |
| Brunori [83] | EuroChoices | Policies | III |
| Centi et al. [84] | Catalysis Today | Processing & Technology | II |
| Charlton et al. [85] | Chemical Engineering Research and Design | Processing & Technology | II |
| Chen [86] | Chinese Journal of Biotechnology | Processing & Technology | I |

*table continues*

| Reference | Journal | Research domain | Category |
|---|---|---|---|
| Chisti [57] | Biofuels, Bioproducts and Biorefining | Environmental impact | II |
| Cichocka et al. [87] | Journal of Biotechnology | Research & Development | I |
| De Jong et al. [45] | Biofuels, Bioproducts and Biorefining | Processing & Technology | II |
| De Meester et al. [58] | Biofuels, Bioproducts and Biorefining | Environmental impact | II |
| Dubois [88] | Current Opinion in Environmental Sustainability | Resources | II |
| Dusselier et al. [89] | Energy and Environmental Science | Processing & Technology | II |
| Ferdinands et al. [90] | Current Opinion in Environmental Sustainability | Resources | IV |
| FitzPatrick et al. [91] | Bioresource Technology | Processing & Technology | II |
| Galvez et al. [92] | Agriculture, Ecosystems & Environment | Environmental impact | II |
| Hardy [93] | Trends in New Crops and New Uses | Policies | I |
| Hatti-Kaul [41] | Crop Science | Processing & Technology | II |
| Hoefnagels et al. [46] | Energy Policy | Economics | II |
| Huang [94] | Botanical Journal of the Linnean Society | Environmental impact | II |
| Jenkins [95] | Biofuels, Bioproducts and Biorefining | Processing & Technology | I |
| Jordan et al. [96] | Science | Resources | II |
| Junginger et al. [97] | Biomass and Bioenergy | Economics | II |
| Keegan et al. [98] | Biofuels, Bioproducts and Biorefining | Processing & Technology | II |
| Keijsers et al. [39] | Carbohydrate Polymers | Resources | II |
| Kgathi et al. [99] | Energy Policy | Social | II |
| Kircher [100] | Biofuels, Bioproducts and Biorefining | Policies | II |
| Kitchen et al. [101] | Local Environment | Social | IV |
| Krigstin et al. [102] | The Forestry Chronicle | Resources | II |
| Landeweerd et al. [103] | Interface Focus | Resources | III |
| Langeveld et al. [104] | Crop Science | Research & Development | III |
| Lehtonen et al. [105] | Environment, Development and Sustainability | Economics | II |
| Levidow et al. [106] | Science, Technology & Human Values | Research & Development | IV |

*table continues*

| Reference | Journal | Research domain | Category |
|---|---|---|---|
| Liu [107] | Biotechnology Advances | Processing & Technology | II |
| Liu et al. [108] | Biotechnology Advances | Processing & Technology | II |
| Lorenz et al. [109] | Trends in Biotechnology | Processing & Technology | II |
| Marsden [47] | Sustainability Science | Social | IV |
| Mathews [110] | Biofuels, Bioproducts and Biorefining | Policies | II |
| Mathews [111] | Biofuels, Bioproducts and Biorefining | Resources | II |
| Müller et al. [112] | Journal of Biotechnology | Processing & Technology | II |
| Murray et al. [40] | New Biotechnology | Resources | II |
| Navia et al. [113] | Waste Management & Research | Processing & Technology | I |
| Nuss et al. [114] | The International Journal of Life Cycle Assessment | Processing & Technology | III |
| Osseweijer et al. [115] | Genomics, Society and Policy | Social | II |
| Paula et al. [116] | Journal of Agricultural and Environmental Ethics | Social | III |
| Ponte [117] | Science as Culture | Social | IV |
| Preisig et al. [118] | Energy Procedia | Research & Development | II |
| Puddister et al. [119] | The Forestry Chronicle | Resources | II |
| Raghu et al. [120] | Current Opinion in Environmental Sustainability | Environmental impact | II |
| Richardson [121] | Environment and Planning C: Government and Policy | Policies | IV |
| Rossi et al. [48] | Biomass and Bioenergy | Social | IV |
| Rüsch gen. Klaas et al. [122] | ChemSusChem | Processing & Technology | II |
| Sanders et al. [123] | Energies | Economics | II |
| Schmid et al. [124] | Bio-based and Applied Economics | Social | III |
| Sheppard et al. [125] | Current Opinion in Environmental Sustainability | Environmental impact | IV |
| Sheppard et al. [126] | Current Opinion in Environmental Sustainability | Environmental impact | III |
| Sheppard et al. [127] | Current Opinion in Environmental Sustainability | Environmental impact | IV |
| Smyth et al. [128] | AgBioForum | Social | II |
| Smyth et al. [129] | AgBioForum | Social | II |
| Spiertz [130] | European Journal of Agronomy | Resources | II |
| Sultana [131] | Biomass and Bioenergy | Resources | II |

*table continues*

| Reference | Journal | Research domain | Category |
|---|---|---|---|
| Tanksale et al. [132] | Renewable and Sustainable Energy Reviews | Processing & Technology | I |
| Templer et al. [133] | Interface Focus | Research & Development | III |
| Ten Bos et al. [134] | Carbohydrate Polymers | Research & Development | III |
| Tsiropoulos et al. [135] | Journal of Cleaner Production | Processing & Technology | I |
| Vaaje-Kolstad et al. [43] | Science | Processing & Technology | II |
| Van Dam et al. [136] | Industrial Crops and Products | Resources | II |
| Vaneeckhaute et al. [137] | Water, Air, & Soil Pollution | Processing & Technology | II |
| Vaneeckhaute et al. [138] | Biomass and Bioenergy | Environmental impact | I |
| Vaneeckhaute et al. [139] | Biomass and Bioenergy | Environmental impact | II |
| Vanholme et al. [140] | Frontiers in plant science | Processing & Technology | II |
| Vitasari et al. [141] | Bioresource Technology | Processing & Technology | II |
| Voll et al. [142] | Biofuels, Bioproducts and Biorefining | Processing & Technology | III |
| Wellisch et al. [59] | Biofuels, Bioproducts and Biorefining | Environmental impact | II |
| Wesseler et al. [143] | AgBioForum | Environmental impact | II |
| Zhang et al. [144] | Current Opinion in Chemical Engineering | Processing & Technology | I |
| Zilbermann et al. [145] | AgBioForum | Processing & Technology | I |

### 2.3.1 Bibliographic analysis

As described in Section 2.2.2, 87 papers were chosen for review. Figure 2.2 shows the spread of the papers over time, presenting the numbers of papers published per year. It stands out that all publications are relatively recent, the oldest one being from 2002. Apart from this oldest paper, all have been published within the last ten years. This shows that the consideration of sustainability in the bioeconomy debate is a relatively new topic. Furthermore, it stands out that the number of publications has increased strongly: from 2002–2007, only 0–2 papers were published per year, which increased to 21 in 2012. Since the papers were selected in June, 2013, the total number for the year 2013 is unclear, but the result of just the first half-year, 17 papers, suggests that a further increase in numbers can be expected. The strong increase in publications indicates a rising attention for the topic.

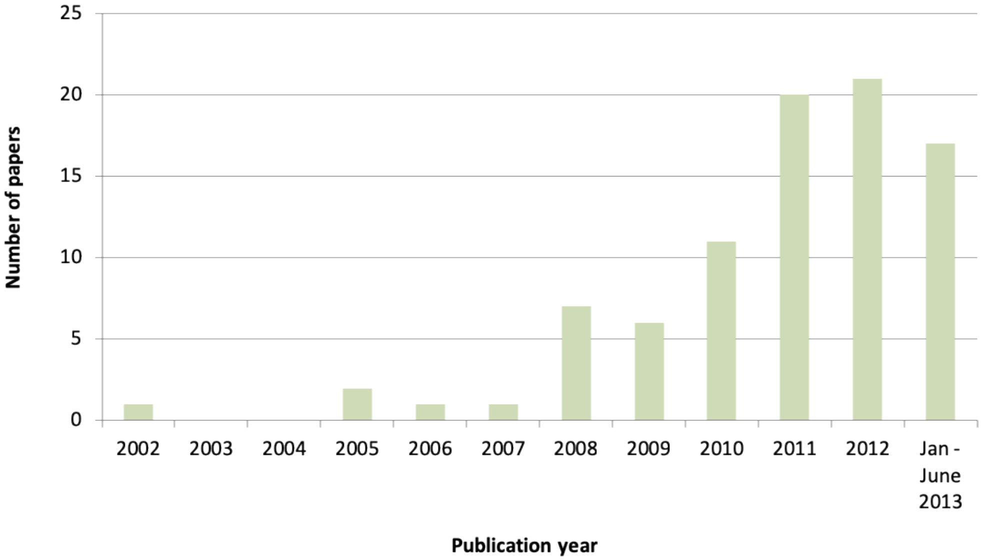


Figure 2.2 Number of papers reviewed published per year.

Figure 2.3 shows the research domains regarding the bioeconomy addressed by the reviewed papers. Seven research domains were identified. Papers falling under the domain "Processing and Technology" mainly describe processing techniques for the conversion of biogenic resources, production pathways for potential bio-products or technology strategies, such as the design of biorefineries. The second domain, "Resources", is comprised of papers discussing the choice and production of biomass resources. Next to the potentials of different feedstock and other biomass sources, also, other aspects, such as land-use efficiency and (agricultural) production yields, are discussed. The majority of publications belong to these first two domains, which are both of a relatively technical nature. Other domains of the bioeconomy were addressed less often and were captured under the headings "Environmental Impacts" (e.g., biosecurity), "Social aspects" (e.g., food security), "Policies" (e.g., agricultural or industrial policies), "Research and Development" agendas (e.g., research programs) and "Economics" (e.g., regional economies).

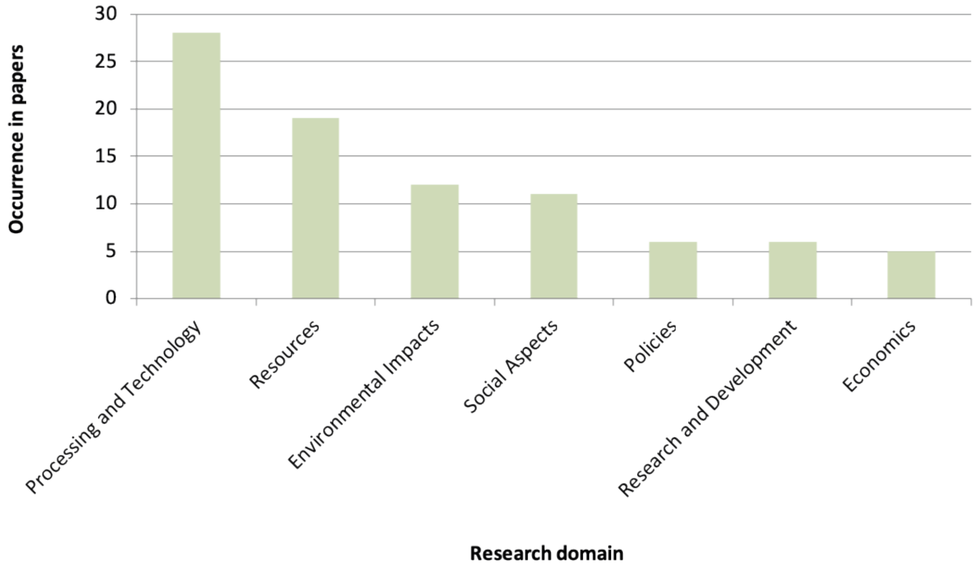


Figure 2.3 Research domains regarding the bioeconomy and their occurrence in the reviewed papers.

### 2.3.2 Sustainability and the bioeconomy

The papers selected for review mention sustainability in some context with the bioeconomy. However, the way sustainability is addressed in these publications differs strongly. Based on these differences, the publications were grouped into four categories that reflect their presumptions of the relation between sustainability and the bioeconomy. The categories are based on descriptions of three important aspects of this relation, which were identified during the review process: contributions of the bioeconomy to sustainable development, conditions or requirements for such contributions to be realised and problems that inhibit a contribution or even have a negative impact on sustainability.

In total, nine contributions, 27 conditions and 14 problems have been described in the reviewed literature (Table 2.2). In each article, one or more of these aspects are present. The connection between the three aspects and the characterisation of the categories is presented schematically in Figure 2.4. In the following sections, the characteristics of all categories will be described.

Table 2.2 Contributions, conditions and problems described in the literature and the numbers of papers that name them, in sum and per category.

| Contribution \| Condition \| Problem | Number of papers | | | | |
|---|---|---|---|---|---|
| | Σ | I | II | III | IV |
| **Contribution** | | | | | |
| Reduction of greenhouse gas emissions | *21* | 3 | 18 | - | - |
| Sustainable production of commodities | *18* | 6 | 12 | - | - |
| General contribution | *14* | 2 | 12 | - | - |
| Sustainable society | *9* | - | 9 | - | - |
| Reduction of negative environmental impacts | *7* | 3 | 4 | - | - |
| Sustainable use of resources | *7* | - | 7 | - | - |
| Sustainable fertilisers | *5* | 1 | 4 | - | - |
| Sustainable energy | *4* | 1 | 3 | - | - |
| Biodiversity | *3* | 1 | 2 | - | - |
| Social equity | *3* | - | 3 | - | - |
| *Possible contribution* | *10* | - | - | 10 | - |
| **Condition** | | | | | |
| Sustainable biomass production | *18* | - | 14 | 4 | - |
| Assessment of production chains and impacts | *13* | - | 11 | 1 | 1 |
| Efficient use of biomass resources: all components and by-products | *13* | - | 12 | 1 | - |
| Assessment of sustainability or application of criteria | *12* | - | 10 | 1 | 1 |
| Sustainability central element in bioeconomy | *12* | - | 7 | 5 | - |
| Efficient use of biomass resources: best application of resources | *11* | - | 8 | 3 | - |
| Sustainable production chains | *10* | - | 9 | 1 | - |
| Research & Development: innovative products | *10* | - | 8 | 2 | - |
| Efficient land-use | *7* | - | 5 | 1 | 1 |
| Public participation | *6* | - | 3 | 2 | 1 |
| Assessment of best biomass sources | *5* | - | 5 | - | - |
| Assessment of efficient biomass use | *5* | - | 5 | - | - |
| Improved agricultural practices | *5* | - | 4 | 1 | - |
| Research & Development: sustainability of bioeconomy | *5* | - | 4 | 1 | - |
| Assessment and management of invasion risks and effects | *4* | - | - | 1 | 3 |
| Regulation: sustainability standards for resources | *4* | - | 4 | - | - |
| Assessment of policy impact | *3* | - | 1 | - | 2 |

*table continues*

| **Contribution \| Condition \| Problem** | **Number of papers** | | | | |
|---|---|---|---|---|---|
| | **Σ** | **I** | **II** | **III** | **IV** |
| Biodiversity conservation | *3* | - | 2 | - | 1 |
| Incentives: sustainable land-use | *3* | - | 3 | - | - |
| International cooperation | *3* | - | 1 | 1 | 1 |
| Reduction of greenhouse gas emissions | *3* | - | - | 2 | 1 |
| Sustainable land-use | *3* | - | 2 | - | 1 |
| Assessment of biomass availability | *2* | - | 2 | - | - |
| Assessment of land-use efficiency | *2* | - | 2 | - | - |
| Incentives: industrial application of biomass | *2* | - | 2 | - | - |
| Socially responsible biomass production | *2* | - | - | 2 | - |
| Sustainable forest management | *2* | - | 2 | - | - |
| **Problem** | | | | | |
| Competition for land | *24* | - | 14 | 6 | 4 |
| Competition for resources | *21* | - | 15 | 3 | 3 |
| Reduction of emissions unclear | *16* | - | 11 | 3 | 2 |
| Contribution to sustainable development questionable | *13* | - | 3 | 2 | 8 |
| Negative impacts on water systems | *13* | - | 8 | 3 | 2 |
| Negative impacts on the environment | *12* | - | 7 | 3 | 2 |
| Negative impacts on soils | *10* | - | 7 | 2 | 1 |
| Negative impacts on habitats and biodiversity | *9* | - | 6 | 2 | 1 |
| Risks posed by invasive species | *7* | - | 1 | 2 | 4 |
| Agricultural intensification | *6* | - | 3 | 1 | 2 |
| Social concerns | *5* | - | 2 | 1 | 2 |
| Risks posed by new techniques and unknown long-term effects | *5* | - | 2 | - | 3 |
| Economic feasibility | *4* | - | 2 | - | 2 |
| Health risks | *2* | - | - | 1 | 1 |

The categories are indicated with roman numerals. If a contribution, condition or problem is not mentioned in any article of a certain category, the symbol “-” is applied.

Each publication has been allocated to one of the categories. The first category contains 12 papers describing the contributions and positive impacts of the bioeconomy on sustainability. The second category, containing 53 papers, is the largest. These publications focus on various conditions that have to be met in order to realise contributions to sustainability and avoid certain problems. The third category comprises 10 papers arguing that a contribution to sustainability is possible, but not necessarily reached. These papers also describe the risks of the development of a bioeconomy in the form of problems and possible negative consequences. The last category contains 12 papers focusing on the negative impacts of the bioeconomy. Some name conditions without stating that they will ensure sustainability, but most only discuss problems of the bioeconomy with regard to sustainability. In the following sections, we describe the categories in more detail.

#### 2.3.2.1 Category I: Sustainability as an inherent characteristic

The papers combined in this first category consider sustainability as an implicit result of the bioeconomy. Developments leading towards a bioeconomy also contribute to sustainability and are regarded as positive. Some speak of the bioeconomy as if it was self-evidently sustainable, for example referring to the use of renewable resources, which are the basis of the bioeconomy, as sustainable [82,113,132,144,145]. Most papers name specific contributions of the bioeconomy to sustainability, which are shown in Table 2.2. The contributions range from sustainable products, such as fertilisers, energy or commodities in general [82,86,87,93,95,132,135,138,144,145], to physical and ecological benefits, such as the reduction of greenhouse gas emissions and other negative environmental impacts [87,93,95,132]. Both Chen [86] and Hardy [93] indicate that the bioeconomy generally contributes to sustainability.

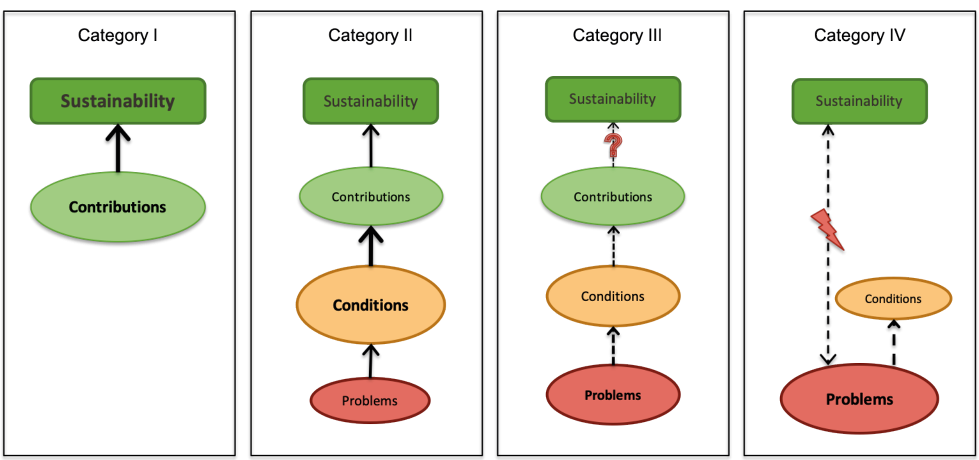


Figure 2.4 Schematic presentation of the four categories of papers, based on the relation between contributions, conditions and problems.

#### 2.3.2.2 Category II: Conditional benefits

The second category comprises papers arguing that the bioeconomy is beneficial for sustainability under certain circumstances. They are generally supportive of a development toward a bioeconomy and argue that it will contribute to sustainability, if certain preconditions are met. Most papers name sustainability, or contributions to sustainability, as positive or desired outcomes of the development towards a bioeconomy. Some mention problems connected to the bioeconomy and especially biofuels, but they subsequently describe measures or strategies to avoid these problems. As in the first category, some papers assume that renewable resources are generally sustainable [59,79,100,122,131,136,140]. Furthermore, 14 papers argue that sustainability should be a goal of the transition to a bioeconomy [57,59,122,130,136,143,71,94,107,108, 110,115,118,120] and seven state that it should be a central element in a bioeconomy [57,59,84,97,98,105,129]. A wide range of conditions is described. Some conditions directly regard sustainable production systems (named in 31 papers), such as sustainable biomass production, sustainable production chains or sustainable land-use. Papers refer to the necessity to reduce environmental impact, increase sustainability in agricultural production and ensure sustainable cultivation and harvesting practices. Other papers claim that efficient use of resources contributes to sustainability, for example efficient biomass or land-use (named in 31 papers). Various papers argue that in order to be efficient, all components of a biomass resource should be used. In some papers, this refers to the use of all the different parts of crops; in others, more specific internal components are named, such as sugars, cellulose or lignin. Often, this efficient use is related to the manufacturing of a broad spectrum of products, in which the different feedstock fractions may serve as inputs for various supply chains. Another important aspect is the re-use or recycling of by-products, residues and waste streams. Often mentioned is, furthermore, the efficient use of biomass in terms of choosing the best application for each quantity of resource. Different feedstock types are more or less well suited for the broad spectrum of products envisaged for the bioeconomy. Choosing the most appropriate feedstock for each supply chain and realising the maximum output from each quantity of biomass makes the resource use more efficient and is described as more sustainable. Other conditions regard strategic aspects (named in 24 papers), such as research and development and incentives or regulations of aspects considered important for sustainability, such as innovative products or stimulation of sustainability itself. Furthermore, international cooperation, public participation and biodiversity conservation are considered important conditions for sustainability (named in three, six and three papers, respectively). Many papers insist that in-depth assessments of various aspects of the bioeconomy have to be carried out (named in 46 papers), for example full assessments of individual production chains and their impact and specific sustainability or efficiency assessments. However, despite their plea for thorough assessments, these papers still remain generally positive about the impact of the bioeconomy on sustainability.

#### 2.3.2.3 Category III: Tentative criticism

The third category consists of publications that have more reservations regarding the bioeconomy. When it comes to sustainability, they consider a beneficial impact possible, but not self-evident. Apart from potential benefits, they also elaborate on problems for which they do not necessarily see solutions. Most of these papers consider sustainability important with regard to the bioeconomy. For example, they name it as goal or argue that it should be given a central role. However, while they appreciate sustainability, they are restrained in approving of all aspects of the bioeconomy. Several conditions and problems are mentioned, as shown in Table 2.2. The most important problem mentioned is the competition for land caused by an increased demand for biomass resources. This problem links up with the well-known "food vs. fuel" debate. It is mainly argued that the agricultural production of biomass for bioeconomic products (mainly biofuels) may be in competition with food and feed production [103,116,134]. The pressure on land is increasing through both biomass demand and population growth [103]. Both direct and indirect effects of land-use change are described. Direct effects can be increased greenhouse gas emissions as a result of the clearing of forests for new production sites, but also resulting from different plantation methods of biofuel feedstock. Indirect effects are caused by the relocation of agriculture for food production to other land surfaces when the original land is used for new purposes within the bioeconomy [103,133]. However, not only competition for land with food production is an issue. Sheppard et al. [126] point out that, also, more marginal lands are used for biomass production. These marginal lands are often valuable for natural functions, such as biodiversity. Another problem described in the literature is that in some cases, bioeconomic production does not reduce greenhouse gas emissions, as expected, and sometimes, this effect remains unclear. Greenhouse gas emissions may result from land-use changes, as described above, but also from energy use in the processing of biomass [103,104,133]. Other problems described in this category are, for example, negative impacts of biomass production on the surrounding environment and water systems. Examples are the destruction of natural ecosystems for new production areas, increased eutrophication, pests related to novel crops that may infect neighbouring ecosystems and high demand for water, resulting in pressure on natural water systems and the ecosystems depending on them [103,104,114,126].

#### 2.3.2.4 Category IV: Negative impact

Papers in the fourth category consider the bioeconomy as disadvantageous for sustainability and do not expect any positive contributions. They are critical regarding expected benefits and focus on problems and risks (Table 2.2). Some formulate conditions without stating that they will ensure sustainability. Richardson [121] argues that the application of renewable resources is often presented as sustainable, and their exploitation is evermore intensified, while in his view, it does not ensure sustainability. Others point out that not all sustainability issues regarding the bioeconomy, such as biosecurity risks, are recognised sufficiently at the policy level, and at the same time, the proclaimed benefits for sustainability are yet unclear [125,127]. Marsden [47] criticises that the bioeconomy paradigm has missing links when it comes to its integration in sustainable place-making. He argues that especially on a regional scale, the bioeconomy is often disconnected from specific aspects of ecosystems and landscapes and, furthermore, poorly embedded in regional social networks. Ponte [117] warns that in a bioeconomy, sustainability labelling may become more important than actually achieving sustainability, as is currently the case with fisheries. Other problems often mentioned by the papers in this category are competition for land, as described under Category III, and risks posed by invasive species. These concerns mainly relate to new crops used for biomass production that can become invasive and, consequently, threaten traditional production systems or natural ecosystems [73,125,127]. Insufficient management of invasion risks, for example, due to uncontrolled cultivation practices, can lead to the spread of the crop species themselves and their associated pests [90,125]. Barney et al. [73] point out that the crops envisioned for the bioeconomy will have a high invasion potential: they are required to be highly productive and, thus, harbour few pests and be competitive with other plant species, which are traits often found in invasive species. Furthermore, yearly harvesting and subsequent transportation may serve as an introduction pathway into other regions and ecosystems.

#### 2.3.2.5 Research domains and sustainability

Figure 2.5 shows the research domains, as described in Section 2.3.1, in relation to the categories distinguished above. It stands out that the first two categories are dominated by the more technical domains of “Processing and Technology” and “Resources”, while the third and fourth category are comprised of a greater variation of research domains. Especially the first category shows a prevalence of one research domain: 67% of the papers deal with “Processing and Technology”. In the second category, papers of all research domains are represented, but the largest groups are “Processing and Technology”, “Resources”, and “Environmental Impacts”. While the research domains in the third category are very diverse, the most important domain in the fourth category is clearly the discussion of “Social Aspects” (42%). Furthermore, it stands out that no papers discussing “Processing and Technology” of biomass focus on the negative impacts of the bioeconomy. At the same time, no papers of the research domain “Social Aspects” see sustainability as an inherent characteristic of the bioeconomy. Papers describing “Research and Development” and “Policy” agendas of the bioeconomy are distributed relatively equally over all categories. All five papers in the domain “Economics” describe a conditional contribution and are inclined to be positive about the sustainability of the bioeconomy. Papers writing about “Environmental Impacts” are represented in all categories, but 67% consider a conditional contribution to sustainability, assuming that under certain preconditions, negative environmental impacts can be avoided.

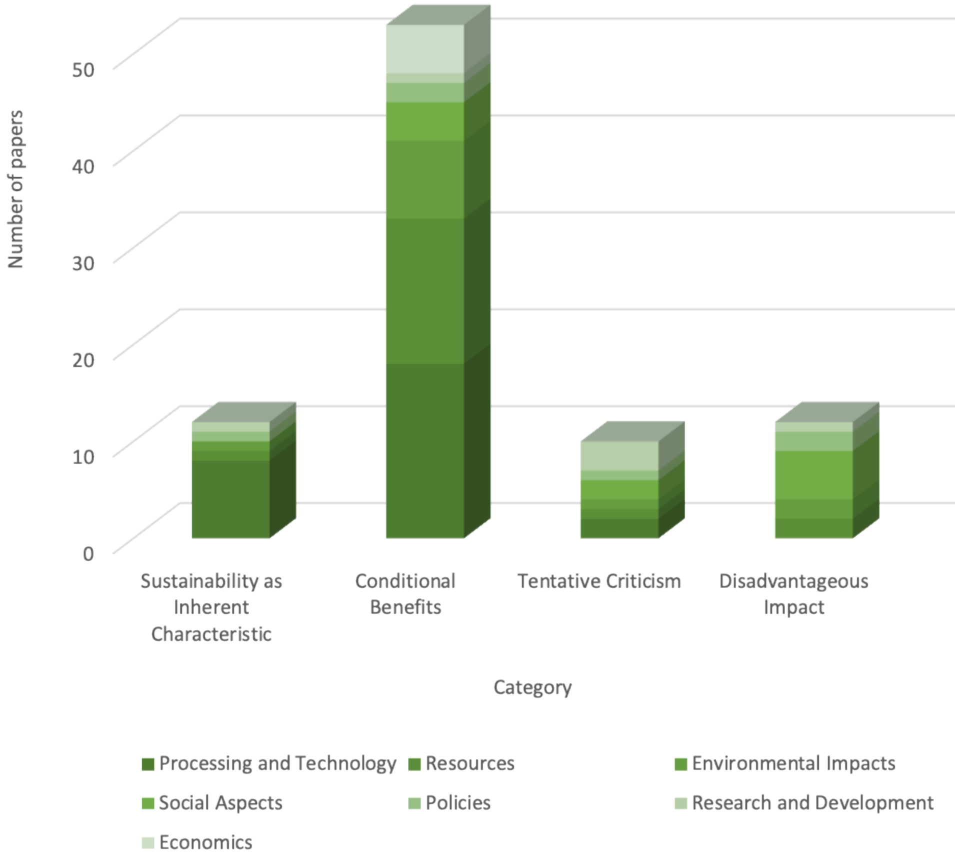


Figure 2.5 Research domains regarding the bioeconomy per category.

The four categories of publications identified in this review range from more positive to more negative views of the effect of the bioeconomy on sustainability. Clearly, the number of publications is highest in Category II, which might be characterised as mildly optimistic. When comparing the average years of publications per category, it appears that the number of critical papers has increased in recent years. However, an upward trend in recent years can be noticed for all categories. Papers from Category IV showed a publication peak in 2011.

In that year, a special issue regarding the invasion risks of new crops in the bioeconomy was published in the journal "Current Opinion in Environmental Sustainability", from which six papers were reviewed here [88,90,120,125–127]. Three of the 12 publications in

Category IV stem from this special issue and are mainly responsible for the peak of five papers in 2011. Nevertheless, also in 2012, four papers of Category IV were published, so an upward trend can be noticed.

### 2.3.3 Strategies for the bioeconomy

In addition to the above-described results, some general observations were made while reviewing the literature. They are concerned with various aspects of the actual development of the bioeconomy. These observations will be described in the following sections.

#### 2.3.3.1 Drivers of the bioeconomy

Throughout the reviewed literature, several drivers for the development of a bioeconomy, or reasons to engage in it, are named. The main driver discussed is the need to reduce our dependence on fossil resources (named in 69 papers). This aspect is of a three-fold nature. First of all, the availability of the resources is uncertain, and it is generally expected to decrease in the near future. Secondly, even if there are no immediate shortages, the remaining fossil fuel reserves are more difficult to reach. Extraction becomes more expensive and bears significant environmental risks, resulting in uncertainties about resource costs. Thirdly, it is pointed out that remaining reserves are often located in geopolitically unstable regions. These factors make it advantageous to find alternatives for fossil resources and, therefore, drive the development of the bioeconomy, where they are replaced with biogenic resources. The second driver discussed is the need to reduce greenhouse gas emissions or carbon footprints, due to the insights about their impact on the global climate system (named in 40 papers). Mostly, this driver is connected with the choice for renewable energy sources, amongst others bioenergy or biofuels. However, also the use of biogenic material in other supply chains reduces the consumption of fossil material and, thus, the release of carbon. Next to these reasons, which are mainly stimulated by the need to reduce the negative impacts of the use of fossil fuels, it is anticipated that the bioeconomy will create further benefits. It is, for example, expected to boost rural development and stimulate rural economies (named in 25 papers). It is assumed that a change of supply sources to biomass results in an increased demand for agricultural or forestry products. This increase of demand may stimulate rural economies and contribute to the social and economic revitalisation of rural communities, including the creation of employment. Furthermore, farmers may take a larger role in supply chains by producing intermediate products and, thus, create additional income. Furthermore, other small suppliers of processing services might play an essential role. Other drivers named in the literature are the secure supply of energy and commodities (named in 23 papers), environmental concerns (named in 19 papers), expected economic benefits (named in 17 papers), an increasing demand for commodities in general and sustainable products in particular (each named in 14 papers), sustainability (named in seven papers) and food security (named in five papers).

#### 2.3.3.2 Food security, marginal land-use and residual biomass

Next to conditions for the sustainability of the bioeconomy, some papers discuss general requirements that should be fulfilled. One is to ensure sufficient production of food. Using biomass resources for the production of biofuels and other raw materials for a bioeconomy is often criticised for its competition with food in the well-known 'food vs. fuel' debate. In the papers reviewed here, different suggestions are made on how to avoid this competition. Some argue that biomass for fuel or material applications should be derived from non-food crops, therefore avoiding direct competition for the same resource [39,111,123]. Others suggest that the amount of land required for sufficient food production should be determined and secured, using the remaining appropriate land surfaces for biomass production for the bioeconomy [99,104]. Again, others state that the total production should be increased [123,130]. Finally, some argue that land surfaces not used or unusable for food production should be used for the production of non-food biomass production [85,111,140]. Generally, the land availability and land-use competition is described by many as a problem or even the limiting factor for the development of a bioeconomy [39,41,85,99,103,104,110,111,116,120,125,126,47,128,133,134,136,48,58,71,74,76,81,84], and the competition with food production is the most described example. An often-suggested solution for the land-use competition is the use of marginal land surfaces for non-food biomass production [84,85,99,111,125,140], avoiding the competition with traditional food production. However, some criticise that also the use of marginal lands is a land-use change and may have negative impacts, for example on biodiversity [120,125,126]. An alternative opted for by some papers is the use of biomass residues, for example the fibrous, non-productive parts of food crops, other agricultural residues or biogenic waste streams from industrial production or private use [39,41,84,95,103,115,136,142]. New technologies are expected to enable the use of, for example, residual lignocellulosic biomass. The use of such residues makes it possible to re-use materials that would otherwise be waste as input for new production chains, resulting in a 'circular' use of resources. Next to the use of biogenic waste, it is also considered important to use all components of any amount of resources, as described in Section 2.3.2.2.

#### 2.3.3.3 Regional scale

One of the most frequently mentioned reasons or drivers for the bioeconomy is rural development, as mentioned above. Next to the expected advantages from rural revitalisation, various papers discuss advantages of developing bioeconomies on a regional scale. Local or decentralised production and processing may save transportation costs and related greenhouse gas emissions and enable a local reuse of by-products [79,82,115,140]. Furthermore, it enables small-scale production, which is expected to be more flexible and stimulate local economic development [79,82,104,105,115,136]. This economic benefit and concentration of incomes to a limited region may furthermore foster social benefits through local employment and a fairer distribution of incomes, and, thus, more equity [82,104,106]. Finally, focusing on specific regions allows for the adaptation to regional characteristics, such as local feedstock. Furthermore, the local knowledge of stakeholders, for example farmers, can provide significant advantages and add to the knowledgebase for the bioeconomy [45,47,81,105,106,124].

#### 2.3.3.4 Integrated approach

As described in Section 2.3.1, the bibliographic analysis confirmed that the sustainability of the bioeconomy is a multidisciplinary field. Various papers emphasise this and furthermore argue that integrated approaches to solve problems regarding the bioeconomy are required. It is acknowledged that the concept of the bioeconomy and related issues are multidimensional [120,124,134,136]. Some papers therefore argue that an integrated or system-based approach is required to understand and address, for example, varying interests and interrelationships of actions and problems [59,120,124,140]. Other papers plead for collaboration between the various disciplines and lines of research involved in the bioeconomy (e.g., agro-ecological research, green and white biotechnology, biofuel research, biology and social science) [120,124,134,140]. Raghu et al. [120] state that multiple perspectives should be considered, avoiding simplistic 'for' or 'against' claims by different disciplines [120 (p. 21)]. In addition to integration between disciplines, papers argue for collaboration with a variety of stakeholders, bridging the gap between science and society. This way, science can link up with societal infrastructure and public interest. Public participation is described as a requirement, but also as an opportunity for a joint production of knowledge [59,115,120,124,134]. Finally, it is stated by three papers that international cooperation is required in order to realise sustainability in the bioeconomy [100,125,126].

## 2.4 Discussion

This paper provides an overview of the scientific debate on the bioeconomy, focusing on how scientific literature relates the bioeconomy to sustainability. Both bioeconomy and sustainability are considered multidisciplinary concepts, and therefore, a broad approach has been taken to include literature from various fields. The wide range of journals with relevant contributions confirms this assumption, and the growth in the number of papers published in the last decade indicates the increasing importance and contemporary nature of this field.

### 2.4.1 The undefined position of sustainability in current research

A majority of the papers consider the relationship between the bioeconomy and sustainability as generally positive (75%, Category I and II). The positive contributions discussed vary from general steps towards a more sustainable economy to specific physical or environmental benefits. Various papers speak of a 'sustainable bioeconomy', without clarifying whether there may also be an un-sustainable bioeconomy. In some cases, the sustainable bioeconomy is mentioned as a goal; in others, the bioeconomy is presented as if it is self-evidently sustainable. Furthermore, in some papers, sustainability is reduced to the choice of renewable instead of fossil resources. They argue that the replacement of fossil materials with biomass automatically contributes to sustainability. However, Richardson [121] and Wellisch et al. [59] contradict precisely this argument, stating, for example, that "…sustainability is not just about renewability or only about the environment or only about GHG emissions." (i.e., greenhouse gas) [59 (p. 284).] According to Wellisch et al. [59], the bioeconomy has the potential to create various positive outcomes and contribute to sustainability, but "…sustainable design must be deliberately planned and assessed." [59 (p. 283).] This points to the importance of giving sustainability a central place in the development of the bioeconomy and considering sustainability in future bioeconomy research.

### 2.4.2 The hegemony of optimism

The papers considering the bioeconomy as generally positive for sustainability are dominated by technical research. Often, the expected contribution underpins the research itself, for example regarding technology developments or crop assessments. However, although technical papers suggest that the bioeconomy is quite sustainable, the more critical publications show that this is not necessarily true. Even though a majority of publications presents a positive picture, most papers (86%) acknowledge problems regarding the impact of bioeconomic activities on sustainability. The discussed problems range from uncertainties and general concerns to measurable negative impacts. Doubts regarding the very goals of the bioeconomy are put forward, stating that the emission reduction promised by biomass is not always realised in practice and that sustainability is not reached. Concerns about uncertainties regarding the impact of invasive species, new technologies, economic feasibility and social impacts are raised. Measurable impacts on mainly the natural environment are discussed, with a special focus on the competition for land and resources. While some papers regard the bioeconomy critically because of these negative impacts, most remain positive despite describing problems. They discuss possible interventions and conditions for a positive outcome and generally still assume that the bioeconomy will contribute to sustainability.

### 2.4.3 Conditions for a sustainable bioeconomy

The conditions for a sustainable bioeconomy that were identified can be organised on the basis of whether they address what one needs to know or do to be sustainable (knowledge or practical application) and whether they restrict or stimulate bioeconomic activities (restrictive or stimulating). For example, some suggest that we have to find out more about sustainability and efficiency of processes through assessments, whereas others suggest that we need efficient applications in practice to be sustainable. Figure 2.6 shows the listed conditions in a matrix with these two dimensions.

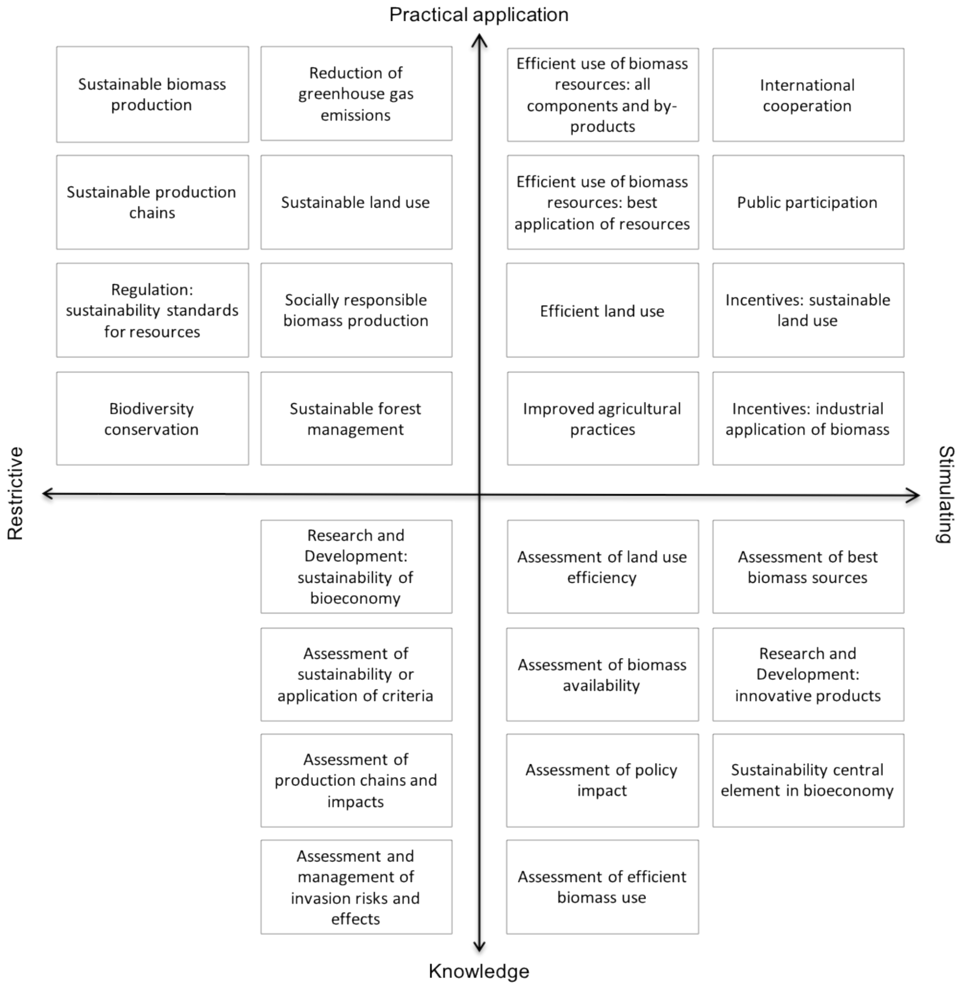


Figure 2.6 The matrix of conditions for a sustainable bioeconomy.

It shows that more conditions are concerned with applications than with knowledge. This could mean that there are already many insights on how the bioeconomy can be made more sustainable in practice. It could also indicate that the bioeconomy is initially addressed in a practical context. Insights gained from practical applications may then be important to improve theoretical understanding, which again calls for transdisciplinary collaboration. Next to conditions regarding applications, the necessity for further analysis is, however, also clearly present. Many papers point out that assessments are required, analysing, for example, sustainability in general or complete production chains. This shows that thorough analysis of sustainability aspects is considered important. Of course, it cannot be concluded that all aspects that have to be considered are named in the literature reviewed. However, the considerable number of publications analysed and the variety of conditions described suggests that Figure 2.6 provides a good picture of the requirements currently recognised for sustainability in the bioeconomy.

### 2.4.4 Sustainability from side to central issue

Looking at the drivers of the bioeconomy named in the literature, it stands out that while some are obviously related to issues of sustainability, such as climate change and its impact on the environment and human wellbeing, many do not directly regard issues of sustainability. The reduction of the dependence on fossil fuels, energy security or the expectation of economic benefits and rural development are, for example, issues that are mostly related to economic interests and not primarily sustainability concerns. It is therefore important to keep in mind the great variety of drivers of the development towards a bioeconomy when considering its sustainability. When striving for a bioeconomy, the contribution to sustainability should go hand in hand with achieving other goals and advantages. Research and policies should focus on how the various goals can be combined to create a bioeconomy that is as beneficial as possible, because otherwise, stakeholders with specific interests may dominate the developments, not necessarily contributing to the public good. An ecosystem services perspective may provide a useful framework to consider the use of biomass resources for various goals, provided that utilisation is realised within the boundaries of sustainability (compare [146,147]).

### 2.4.5 Decentralised organisation fits sustainability

Rural development has been described as one of the most important drivers of the bioeconomy (see Section 2.3.3.1). Mostly, this relates to the increasing demand for biomass resources in general, which are mainly produced in rural areas. Moreover, it is discussed that benefits for rural communities can be promoted further by a decentralised organisation of the bioeconomy. Other expected advantages are saving transportation costs and related emissions, enabling local reuse of by-products, flexible small-scale production that stimulates local economic development, social benefits of local employment, increased equity and adaptation to regional characteristics, taking into account local knowledge. Regarding sustainability, especially the reduced transportation emissions, the reuse of nutrients from by-products and the social benefits stand out. The total amount of carbon emissions from production through processing and use may be reduced, lowering the overall carbon footprint. Looking at the fact that many critical papers articulate doubts about the efficiency of greenhouse gas emission reduction by biomass use, decentralised organisation could provide an advantage. Local economic development and the creation of employment possibilities contribute to social sustainability. Decentralised pre-treatment or even processing of biomass resources can play a significant role in this, enabling rural communities to be more than mere producers of primary resources. If more steps of the supply chains are undertaken in a decentralised way, incomes may be distributed more equally.

#### 2.4.6 Food vs. fuel in the short and long run

On some aspects, the reviewed publications disagree or even contradict each other. In Section 2.3.3.2, we already mentioned the varying points of view on the use of marginal land and residual biomass. It seems that the costs and benefits of these approaches are not yet sufficiently clear and should be analysed further. Regarding the food vs. fuel debate, arguments vary strongly. Some of the papers state that the high food prices in 2008, which are often used as the main argument in the debate, were not (primarily) caused by the competition with biofuel production [111,128], and especially in developing countries, the competition is considered harmless [99,110]. Nevertheless, 28% of publications consider land-use competition a major problem. Some even argue that land availability will be the limiting factor for the development of the bioeconomy [58,71,81,116]. Research focusing on more effective production, processing and use is expected to defuse the conflict over land and resources. However, considering the growing importance of biomass resources and the ever-growing demand for raw materials, it is argued by some that increased efficiency and the utilisation of marginal lands and biomass residues will not suffice. Agricultural production for non-food applications will still be needed, and if all valuable land is reserved for food production and only the least productive parts of plants and residues are used for other supply chains, the demand cannot be met.

### 2.4.7 The plus of transdisciplinarity

Despite these contradictions in the literature, there appears to be relatively little debate about the characteristics of the bioeconomy itself. Most publications describe it as a broad field. The bioeconomy is currently mainly approached in a multidisciplinary way: a broad array of research fields is represented, and the importance of other disciplines is recognised. However, many argue that more integrated, interdisciplinary or even transdisciplinary approaches are required to address the issue appropriately. According to some papers, the integration of knowledge from various disciplines is crucial to achieve a sustainable bioeconomy, and also, policies regarding the bioeconomy should adopt a broader and more integrated scope [59,120,124]. Therefore, future research should not only recognise the breadth of the problem, but also incorporate insights from different fields and contribute to joint knowledge production. The impact of the bioeconomy on sustainability is addressed in various disciplines, as shown in this review. The discussion about the sustainability of the bioeconomy might actually provide a common focus for collaboration between disciplines and with societal stakeholders, but the varying visions of researchers have to be taken into account.

### 2.4.8 Feasibility and impact

In general, it stands out that most reviewed papers were published very recently (within the last decade) and are dominated by technically focused research. These technical papers mainly assume that the bioeconomy will contribute to sustainability, in contrast to socio-economic papers that tend to be more sceptical. Critical research has on average been conducted in later years than papers assuming a positive impact of the bioeconomy. Taken together, these results suggest that scientific debate about the bioeconomy, specifically in relation to sustainability, is still at an early stage. Building upon the expectation that it will be beneficial, research is focused more on the technical feasibility of the bioeconomy, rather than on its actual impact. However, even though the emphasis of research may lie in technical issues, the discussion is already clearly broadening to include various external effects and conditions for sustainability.

### 2.4.9 Elaborating sustainability

Sustainability of the bioeconomy is considered important by several of the publications reviewed. Seven point it out as one of the reasons to engage in the bioeconomy [44,48,59,115,116,125,140], eleven argue that it should be a central element [57,59,129,83,84,97,98,104,116,124,126], and 22 state that it should be the goal of the bioeconomy [57,59,115,116,118,120,122,124,130,132,136,142,71,143,144,94, 103,105,107,108,110,114]. Wellisch et al. [59], however, point out that specific sustainability goals within the bioeconomy are often not clearly defined [59] (p. 282). Throughout our review, we found that sustainability is addressed regularly, but seldom defined or specified. It may therefore be necessary to elaborate specific sustainability goals of the development towards a bioeconomy, together with ways to ensure beneficial practices. The conditions and expected contributions presented in this review are a useful starting point for such considerations. This paper confirms some conclusions of other researchers addressing the effect of specific approaches within the bioeconomy on sustainability or the role of sustainability in policy documents regarding the bioeconomy, as mentioned in Section 2.1. De Meester et al. [58] and Wellisch et al. [59] conclude that biorefineries are potentially beneficial, but stress the importance of sustainability goals, assessments and regulations. These aspects are also represented in the various conditions named in the literature reviewed. Chisti [57] states that a bioeconomy can in principle be sustainable, but only if sustainability is a central objective of the economy itself. The varying views on the sustainability of the bioeconomy presented in this review confirm that a bioeconomy is not necessarily sustainable and that the consideration of sustainability is of great importance. Regarding policy documents, it has been concluded that sustainability plays a subordinate role in comparison to the goal of economic outputs and technological fixes for current problems [60–62]. It is argued that sustainability should be integrated more strongly in policy approaches for the bioeconomy. In many scientific publications, the importance of sustainability is recognised, but not necessarily a central topic. In research, as well as policy development, therefore, more attention should be paid to the impact of the bioeconomy on sustainability.

## 2.5 Conclusions

This review showed that visions about the relationship between bioeconomy and sustainability differ across scientific publications. Four categories of papers were identified that reflect the different visions on this relationship present in the literature, ranging from positive to negative: the assumption that sustainability is an inherent characteristic of the bioeconomy; the expectation of benefits under certain conditions; tentative criticism; and the expectation of a negative impact. The variety of problems and conditions shows that the bioeconomy cannot be considered self-evidently sustainable. Various risks and potential pitfalls have to be considered and avoided. Based on the results of this review, it can be concluded that there is considerable attention for sustainability in the scientific bioeconomy debate. Many publications state that sustainability should be a central topic on the research agendas for the bioeconomy or even be the goal of bioeconomic developments. Even though the bioeconomy might contribute to a more sustainable future in various ways, a positive impact is not self-evident. If sustainability is, however, considered a central goal of the bioeconomy, there may be a good chance of achieving a positive environmental and social impact, while ensuring economic growth through innovative products and the preservation of traditional sectors, such as food production. The economic outputs also may create social benefits. It is also important to consider the interrelationship between various sectors participating in a bioeconomy. By now, there seems to be a focus on discrepancies between sectors, mainly based on the competition for land and resources. However, especially cross-sectoral and interdisciplinary solutions are promising. Because bioeconomy research can be considered a multidisciplinary field, stronger recognition and consideration of insights from other disciplines and stakeholders is necessary to build up a joint knowledgebase and tackle sustainability issues. To realise a contribution to sustainability, thorough assessments of different supply chains are required. It is important to analyse all activities within the bioeconomy, for example, using lifecycle analysis tools, to value their contribution to sustainability. However, such assessments should not only evaluate existing processes, but should also be used to choose the most beneficial applications for the future bioeconomy, so that an optimal contribution to sustainability can be reached. Throughout the reviewed literature, various positive expectations, requirements and potential pitfalls have been identified, but most publications consider only very few of these. Based on the findings of this review, we recommend approaching the bioeconomy systematically and in interdisciplinary or transdisciplinary settings. The knowledge and insights from all related disciplines and stakeholders should be taken into account and translated into new research questions and policy interventions. Various disciplines already discuss the impact of the bioeconomy on sustainability, though visions of this relationship differ. The importance of sustainability is, however, broadly recognised and could thus provide common ground for collaboration and the development of a joint vision for the future bioeconomy.

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# Chapter 3

## Biogas between renewable energy and bioeconomy policies – opportunities and constraints resulting from a dual role

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## Abstract

Background

Biogas plays a major role in two policy domains: the renewable energy domain and the bioeconomy domain. The purpose of this paper is to examine the relationship of current biogas practices with the two policy domains and to identify how biogas can contribute to both. It is based on an analysis of views and ideas gained in a large European project addressing different aspects of biogas production and application, gathered through interviews with a variety of stakeholders involved in the project.

Results

Current practice shows opportunities for biogas to contribute to both domains. Biogas production is an efficient way of using especially residual biomass and can provide multiple products for both policy domains. Biogas can function as a system service provider in the renewable energy domain and various products of the biogas production chain can serve as input for bio-based products. However, the diverging goals of the two policy domains and associated instruments currently hinder the development of innovative connections between them.

Conclusions

The focus on biogas for energy as single main product should be diversified towards creating multiple products and using biogas optimally through innovative solutions. To maximise the contribution to both policy goals, policy makers should jointly aim at optimal use of biomass for multiple goals. Policies should aim at improving the competitive position of biomass-based products over fossil-based products and optimising the use of biomass resources, rather than inciting competition between the different biomass applications.

## 3.1 Introduction

Biogas plays a major role in relation to two different, but interconnected, policy goals currently pursued by the European Union and its member states: increasing the share of renewable energy and achieving a transition towards a bioeconomy. These two policy domains partly overlap where they are concerned with the same resource, biomass, but different applications. This overlap results in a competition between policies over scarce biomass resources. The purpose of this paper is to examine the relationship of current biogas practices with the two policy domains and identify how biogas can contribute to both policy goals, maximising the efficiency and sustainability of biomass use. Empirically, it is based on data collected through interviews with project partners in the Dutch-German INTERREG project “Green Gas”. The project partners, addressing a great variety of topics related to biogas production in this project, can all be considered stakeholders involved in current practice in the biogas sector.

We first review the goals and drivers of the two policy domains in the EU, Germany and the Netherlands and elaborate on the position of biogas within them (Section 3.2). We then analyse the scientific debate regarding the position of biogas in the two policy domains (Section 3.3). In Sections 3.4 and 3.5 we present our research and explore current biogas practices with regard to both policy domains. We discuss the opportunities identified by practitioners to contribute to the different goals as well as the constraints they encountered. In a concluding Section (3.6) we discuss the most promising ways for biogas to contribute to the both policy goals in the future and give recommendations for aligning policies in the two domains.

## 3.2 Dual role of biogas in policy goals

Following the Renewable Energy Directive (RED), the European Union aims at a 20% share of renewable energy in the total energy consumption in 2020 [148]. Important drivers for renewable energy policies in Europe are security of energy supply, related to dependence on oil and gas exporting countries, concerns regarding nuclear energy, and the impact of greenhouse gas (GHG) emissions on the global climate [46,149–153].
Electricity and heat production from biogas are important building blocks to achieve

the European 20% goal. In 2014, biogas accounted for 6.4% of all renewable electricity production in the EU 28 [154]. In Germany and the Netherlands biogas contributed to renewable electricity production for 16.8% and 10.6%, respectively, in 2015 [155,156]. Germany is the European leader in biogas production with around 8900 installations in 2015 [157], mainly due to the introduction of performance subsidies [1] that were relatively high in comparison with other countries until 2012 [158,159]. The high contribution of 16.8% to overall renewable electricity production shows the important position of biogas in the German renewable energy strategy. Biogas is considered a versatile form of energy, since it can provide electricity and heat and can be stored and distributed via gas pipelines. Storage offers the potential to buffer fluctuations in the provision of photovoltaic and wind energy [153,160,161]. Figure 3.1 schematically shows a biogas production chain with typical routes for energy production. Especially heat production from biogas has a high potential to reduce $CO_2$ emissions [153]. In the Netherlands, support for biogas production has been described as a 'rollercoaster' [151]. It was initially aimed at treating waste streams such as manure and organic waste and not seen as a promising technology for energy production. The sector suffered from political and financial uncertainties until regulations and subsidy regimes were altered in 2003-2004 [151,162]. This is reflected in the relatively low contribution of biogas to Dutch renewable electricity production (10.6%). Later, the introduction of a fixed-premium subsidy enabled the development of biogas and green gas projects, but a finite budget for this subsidy and a first come, first served granting system made it less reliable for both businesses and investors than the German subsidy system [163]. In the last few years, renewable energy policies focused mainly on heat production from biomass and the combination with carbon capture and storage (bio-CCS) [164,165].


Figure 3.1 Schematic representation of typical biogas production chains.

[1] The term 'subsidy' is commonly used for any kind of financial support by government, whether it involves a transfer of funds from government to the receiving party or a (partial) waiver of taxes or a lower than normal rate payable for government services by the subsidised party. In this paper, we use the term 'subsidy' to refer to instruments installed to bridge the gap between the market price for energy and the (higher) cost of energy production from biogas. The financial support to bridge this gap can be realised with different instruments (e.g. performance subsidies or market premiums). Currently, these instruments differ in Germany and the Netherlands.

The EU, Germany and the Netherlands have published strategies for a so-called 'bioeconomy', where biomass replaces fossil resources for a great variety of applications, including not just bioenergy, but also bio-based materials [1,2,166]. Important drivers in the bioeconomy policy domain are the need to reduce dependence on fossil fuels, reduction of GHG emissions, secure supply of energy and commodities, and an expected boost for economies in general and rural areas in particular [1,2,9,167,168]. These drivers partly overlap with the drivers for renewable energy policies (security of supply and reduction of GHG emissions) but also feature some additional aspects. Bioeconomy policies do not exclusively focus on bioenergy, but also on other biomass-based products, for example replacing fossil resources in material production and securing commodity supply. In Western Europe, hopes are high that high-tech, bio-based products will create economic revenues [62]. There are no subsidy schemes aimed directly at biogas production in the bioeconomy domain; biogas production is only stimulated from a renewable energy perspective. In Germany, in reaction to sustainability issues and the food *vs.* fuel debate, research and development policy specifically focuses on the use of residual biomass for biogas production and the integration of biogas in the bioeconomy through cascading and biorefineries [169]. In the Netherlands, an academic and societal debate around different biomass applications has evolved in the last years. On the one hand, it is argued that bioenergy is extremely important to reach renewable energy goals and mitigate climate change [150]. On the other hand, bioenergy is heavily criticised as being inefficient in actually reducing carbon emissions and competing with other land-uses [28]. It is argued that while there are other sources of renewable energy, fossil resources as raw material for the production of various materials can currently only be replaced by biomass [28]. In current bioeconomy policies bioenergy is included as one of the products, but it is viewed as the least valuable utilisation of biomass [166,168,170]. Different concepts, such as cascading principles, biorefineries or prioritisation according to the value of the end product are discussed. Generally, these concepts aim at using biomass resources efficiently for multiple products and favour higher-value applications. Biogas for electricity and heat production is often ranked particularly low in this context.

While the different applications compete for the same resource, they may also face similar problems regarding, for example, resource availability, and may thus be able to profit from joined undertaking. This may offer various synergies between policy domains.

## 3.3 Between renewable energy and bioeconomy

In the scientific literature, several issues regarding biogas are discussed that relate to this position between different policy domains. We summarise the debate under the following headings: resources, technology, products, and financing and regulations.

Resources

Various biomass resources can be used as a feedstock to produce biogas. The majority of biogas installations in the EU currently use energy crops, such as corn, as a co-substrate together with manure [171]. But due to high corn prices, competition for land and ethical considerations, some argue that residual biomass resources should be preferred for energy production, while cultivated biomass, which is generally of a higher quality, should be used for other purposes [cf. 33]. Other proposed routes are focusing on the production of multipurpose biomass, aiming to overcome the food *vs.* fuel debate through the provision of multiple products from agricultural biomass [172], and the adoption of multi-feedstock technologies that allow for the use of both waste and agricultural biomass, depending on local resource availability [173].

Products

Biogas can be used to produce energy in different ways. As an alternative to the production of electricity and heat in combined heat and power (CHP) units, biogas can be upgraded to 'green gas' (or biomethane), which is gas with a higher methane to carbon dioxide ratio. For example, carbon dioxide in biogas can be converted into methane through methanation reactions adding hydrogen. The hydrogen needed for these reactions can be produced with power-to-gas technology [174–176]. Through the conversion, the methane content in the gas is increased, which makes green gas compatible with natural gas. It can be fed into the natural gas grid and thus replace natural gas [174]. The sustainability of green gas, (partly) replacing natural gas has been shown to be perceived as positive by the Dutch public [177]. Not only does green gas enable energy applications in other locations and at other times, it also provides an interesting link to other sectors, where natural gas is currently used as a source of methane for the production of chemicals. Using biogas or green gas based on residual biomass for the production of chemicals could increase the societal acceptance of bioeconomy products [178].

Technology

Most biogas installations produce biogas with a methane to carbon dioxide ratio of 60 to 40 as main valuable output, which is subsequently converted into energy in CHP units [140,171]. The technology of biogas production is still under development, aiming at higher biogas yields. However, it is argued, that rather than focussing on increasing biogas yield, innovative technologies should be applied to produce multiple products. An example is the treatment and use of digestate, the residue remaining after processing in the biogas reactor, as synthetic fertiliser substitute. This way, biogas installations could be integrated in small biorefineries, a concept which is increasingly appreciated in the development of a bioeconomy [82,138]. Moreover, the decentralised production of biogas becomes more economically viable through integrated production systems [173].

Financing and Regulations

Currently, subsidies for biogas production are provided in the renewable energy domain. Other applications of biogas do not enjoy the same financial advantage. Production of green gas as transportation fuel has to comply with sustainability regulations defined in the European RED[2], while bio-based products are not yet subject to comparable regulations. Some biomaterial applications can be realised despite the unfavourable financial situation, but this is expected to result in a competition over resources that increases feedstock prices, which in turn strongly influence the economic viability of applications [179]. Both energy and material applications furthermore face different types of regulations, for example regarding feedstock requirements or waste treatment regulations [158,180].

## 3.4 Research approach

To analyse the current practice of biogas production and its position between policy domains, we analysed the results and experiences gained in the Dutch-German INTERREG IV A project "Green Gas". This European transboundary project started in 2012 and was finalised in June 2015. It consisted of 16 subprojects with a great

[2] The RED specifies legal sustainability criteria for biofuels and liquid biomass (Article 17). Biogas thus does not fall under these regulations. However, the sustainability criteria do apply for all transportation fuels, including green gas (Article 2.i). Green gas to be inserted into the gas grid as a replacement of natural gas thus has to be certified, for example by NTA8080 or ISCC.

variety of project partners including research institutes, governmental organisations and private sector organisations from both Germany and the Netherlands. The Green Gas subprojects addressed different aspects of biogas production and application in Germany and the Netherlands, aiming to advance the biogas sector. Most subprojects focussed on the possibilities of green gas applications and the use of residual biomass resources. The diversity of subproject aims provided the possibility to gain a comprehensive overview of current biogas practice.

We conducted semi-structured interviews with project partners from the different subprojects. A total of 15 interviews with partners from 14 subprojects were carried out in 2014. We interviewed the project leaders of these subprojects, as shown in Table 3.1. They were chosen as interview partners because they had comprehensive knowledge of their own subproject and worked in close interaction with project partners from research institutes, private sector and governmental organisations. Furthermore, they were also able to reflect on the experiences gained in other subprojects in which they were involved as project partners. The interviews were concerned with the views and ideas of the interviewees regarding the relationships of current biogas practices with the renewable energy and bioeconomy policy domains. The interviewees were regarded as stakeholders involved in current practice in the biogas sector, not necessarily as policy experts, but knowledgeable on the impact of current policies.

Table 3.1 Goals and results of the Green Gas subprojects and information on the interviewees. Subproject leaders are marked with an asterisk (*).

| **Subproject Name & Short Description** | Background Interviewees |
|---|---|
| *New generation biogas digesters*: optimising all process parameters in biogas digestion for more biogas production, higher economic returns and reduced environmental impact. Comparing different thermal and chemical pre-treatment options for residual biomass streams. Modelling fluid dynamics in digester. | * Project developer; HoSt (Industry, NL)<br>Researcher; Saxion University of Applied Sciences (NL)<br>Researcher; Münster University of Applied Sciences (GER) |
| *Mechanical and enzymatic pre-treatment of organic residues*: Testing different mechanical and enzymatic pre-treatment options on various ligno-cellulosic substrates, focusing on biogas return, energy use and cost reduction. | * Researcher; Münster University of Applied Sciences (GER)<br>Director; DNL contact (Industry, GER) |
| *More divers resource use focussing on sugar beet*: Assessing possibilities to use sugar beets instead of maize in biogas installations. | * Project coordinator; Centre of Competence 3N (Industry, GER) |
| *Biogas collection as connection between green gas producers*: Analysing possibilities to connect biogas producers via a biogas net and centralised green gas production. | * Consultant; Ekwadraat (Industry, NL) |
| *Natural grass chain*: Improving biogas technology from pre-treatment to post-treatment to enable utilisation of natural grass and roadside vegetation. Technological and economic analysis. | * Managing director; Byosis group (Industry, NL) |
| *Information exchange via potential map*: Plotting information relevant for biogas development (e.g. existing biogas installations, biomass potentials, energy demand) on an interactive, web-based map to enable more biogas projects in the future. | * Public servant; Province of Groningen (Governmental Organisation; NL)<br>Researcher; Münster University of Applied Sciences (GER) |
| *Green Gas InNet*: Comparing different applications of biogas regarding e.g. GHG emission reduction potential and technical and juridical conditions. Analysing possibilities to feed green gas into the natural gas net. | * Researcher; Münster University of Applied Sciences (GER) |
| *Green Gas in spatial energy concepts*: Analysing possibilities for biogas in joint energy management in industrial areas | * Researcher; University of Oldenburg (GER) |
| *Assessment and Management of Green Gas Supply Chains*: Technical benchmarking of biogas installations, identifying key levers for efficiency and environmental performance. | * Researcher; University of Oldenburg (GER) |
| *Waste Water Treatment Plants as part of Green Gas Hubs*: Optimising sludge digestion in combination with waste water treatment, looking e.g. at processing, energy use, pre-treatment options. Analysing alternative options of using existing sludge digesters, e.g. using other feedstock. | * Researcher; Saxion University of Applied Sciences (NL)<br>Researcher; Saxion University of Applied Sciences (NL) |

*table continues*

| **Subproject Name & Short Description** | Background Interviewees |
|---|---|
| *Cheap resources and Sabatier process*: Analysing possibilities to improve the overall business case for biogas and looking for better technologies to upgrade biogas to green gas. | * Director; Hanze Welands (Industry, NL) |
| *Biogenic methane production from hydrogen and German-Dutch database biogas research*: Analysing technical possibilities to realise biogenic methanisation to create $CH_4$ from $CO_2$ and $H_2$ as alternative for catalytic methanisation. Developing an open source database for biogas literature in three languages. | * Researcher; Münster University of Applied Sciences (GER) |
| *Decentralised energy landscapes Germany – Netherlands*: Integrated assessment of the use of residual biomass for biogas production. Focusing on sustainability and feasibility assessment of complete biogas supply chains, integration in regional context and landscapes. Analysing potential of using various residual biomass streams in biogas digesters. Investigating the potential of applying public-private partnerships for the use of residual biomass for biogas production. | * Personal participation, Radboud University Nijmegen (NL)<br>Researcher; University of Oldenburg (GER) |
| *International trade of Green Gas via certificates*: Comparing policies for biogas and green gas in GER and NL and modelling possibilities of harmonising international policies. Analysing possibilities of improving international trade of green gas via certificates, comparing existing certification schemes. | * Project coordinator; JIN (Industry, NL) |

The interviews were analysed in line with a thematic analysis approach. We used the qualitative data analysis (QDA) software package ATLAS.ti (version 7) to identify common themes in the interviews, coding the transcripts in several steps. The interview questions were based on the topics derived from the literature as discussed in Section 3.3 (Resources, Products, Technology, Financing and Regulations) and addressed context, goals and results of the individual subprojects, the experience of project partners regarding current practices, their views on the potential of biogas production, and the relationship between biogas and the policy goals of renewable energy production and the bioeconomy. In Sections 3.5.1 – 3.5.4 we present the common themes identified in relation to each topic.

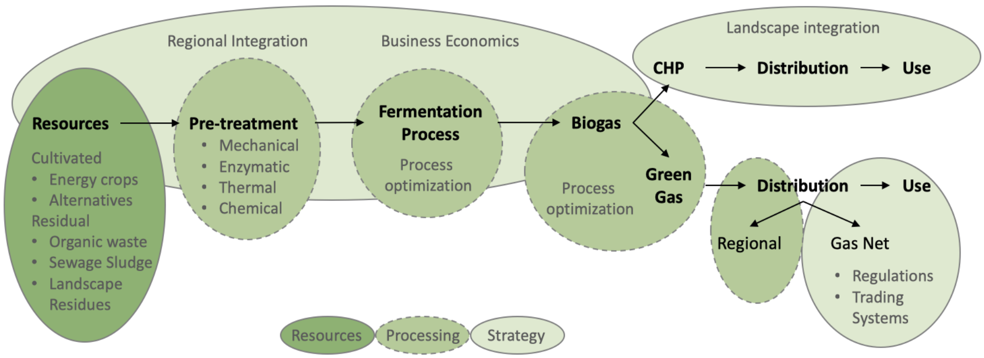


Figure 3.2 Topics addressed in the Green Gas subprojects.

Figure 3.2 shows the various topics addressed in the Green Gas subprojects and their relationship to a schematic biogas supply chain, incorporating various options of feedstock choices, processing steps, and distribution pathways. The fact that this project addressed so many different aspects of biogas is of particular value regarding the goal of this paper, since opportunities and constraints may be found along the whole biogas supply chain. All subprojects considered biogas production in co-production facilities, using animal manure in combination with a co-product as feedstock. Only the feedstock choice for the co-product is depicted separately in this figure. Mono-digestion of manure receives a lot of attention in the Netherlands, but since manure is currently not considered as feedstock for bio-based products, there is no competition between bioenergy and bioeconomy applications. Therefore, we do not consider biogas production from mono-digestion of manure in this paper, but rather focus on the competition over biomass that serves as co-products in biogas production. The subprojects are briefly introduced in Table 3.1. More information can be found on the project website[3].

## 3.5 Results and discussion

In this section we present the results of our analysis, organised according to the four headings described in Section 3.3. Under each heading, we will first describe the views and expectations of the interviewees and subsequently interpret and discuss them in relation to the position of biogas between the renewable energy and bioeconomy

[3] http://groengasproject.eu/

policy domains. We will refer to one (1), some (2-7), or most (>7) interviewees expressing a certain view or experience. Most issues were raised by only a couple of the 15 interviewees, which can be explained by the differences in project focus and background. Finally, in Section 3.5.5 we will provide an overview of our results.

### 2.5.1 Resources

Some interviewees point out that there are currently biomass resources available that are underused. While processing routes and markets for bio-based products are still under development, biogas production is currently feasible and could make use of such resources, for example: manure, landscaping residues, agricultural residues, catch crops, and biomass from field borders. Some interviewees suggest that resources should not be wasted while waiting for innovative technologies, but used now for applications that are already developed, such as biogas production. Furthermore, they expect that the demand for biomass created when biogas production is increased will also help to mobilise the provision of more biomass resources. The supply of biomass is still underdeveloped and increased demand could be an incentive for more and better harvesting and logistic structures, increasing the availability of resources not only for energy production but all biomass applications. According to interviewees, improved logistics may also include new types of contracts to enable cost effective biomass management, for example parties that maintain landscapes for free in exchange for the right to harvest, use or sell the biomass growing there.

Some interviewees suggest that biogas production can become an added value for waste processing. It can be used to process organic waste streams, creating added value through the production of energy and, in the future, extraction of valuable components. Interviewees expect that even if the focus may shift towards other products in the future, unusable waste streams will always remain that can be used for energy production.

#### Discussion: Towards low-value biomass

These suggestions show the rise of a new perspective on resources in current biogas practice, focusing on biomass that is less attractive, less readily available and more difficult to process. Until now, the choice of resources was mainly focused on high energy food crops, enabling a high return of biogas per tonne. Rising prices for traditional biogas co-substrates, such as corn, and the food *vs.* fuel debate appear to force the sector to look for alternatives. Moreover, the upcoming bioeconomy, where higher value products from biomass are expected to be developed, forces the biogas sector to look for different resources such as residual biomass. The switch from high energy food crops to residual biomass is not a new idea, it reflects a movement in the biofuel sector from first generation biofuels (produced from food crops) to second generation biofuels (produced from energy crops and residues) and a preference for residual biomass that has also been discussed for the broader bioeconomy [33,36]. However, while this switch has been approached from a sustainability perspective in the scientific debate, in biogas practice economic incentives appear to be at least as influential. From a renewable energy perspective, optimal biogas production would be achieved with high-value biomass, but in practice it is expected that these resources will become the main feedstock for bio-based products. Thus, the perspective of the bioenergy sector moves away from choosing the best feedstock towards trying to find appropriate processing for otherwise unusable resources. This may reduce the energy output but could increase the overall benefit gained by using all resources efficiently, either for energy or for bio-based products.

### 3.5.2 Products

All interviewees were asked to reflect on the choice between using biogas to produce electricity in CHP units and upgrading biogas to green gas. Their comments showed that biogas is generally applied locally, whereas green gas is sold nationally or even internationally. The markets for biogas and green gas differ and the choice should be made based on local conditions. One of the most important considerations is the vicinity of consumers: in CHP units both heat and electricity are produced. While electricity can be fed into the grid and thus distributed easily, heat has to be used locally in a considerable proportion. Next to the heat used in the installation itself, the ability to sell heat in the vicinity is of great importance for the business case of biogas installations. An alternative that has been considered in one of the subprojects is to set up a regional network specifically for biogas, enabling the transport of biogas to locations where a CHP unit can serve both electricity and heat consumers. However, this appeared to be expensive and difficult to realise. Green gas offers the advantage of wider application; it can be fed in where it is produced and used where it is needed (provided access to the gas grid is in reasonable proximity, for example by choosing the location for upgrading installations strategically). Furthermore, the gas is storable (in the grid or otherwise) and can be used when needed, while CHP units always produce heat as well as electricity, even when the heat cannot be used (e.g. when there is little demand at night or in the summer). The biggest disadvantage of green gas is, according to interviewees, that it is very expensive to upgrade, requiring high investment costs up front. Furthermore, for feed-in strict quality standards apply for green gas and sometimes conditions are unclear or changing. Some interviewees describe that some network operators in the Netherlands are not keen on accepting green gas, setting up conditions that are difficult to meet. Some interviewees emphasised that biogas can best be applied regionally, but the application has to be adapted to the geographical, demographical and political landscape. Biogas is considered useful to create and keep value in a certain region, but if regional use is not possible, green gas becomes more attractive and useful.

All interviewees emphasised advantages biogas can offer for the energy system. First of all, they described the potential for biogas to be a 'system service provider' for the electricity system. Electricity from biogas could be used complementary to other renewable energies, providing power when the sun does not shine and the wind does not blow, buffering oscillations in electricity production. However, it does not fulfil this function at the moment. Subsidies for renewable energy production are always paid when electricity is produced and fed into the grid. It is therefore most convenient to have the system running continuously. Biogas could be stored for at least some hours (e.g. in the digesters, as green gas in the grid, or in storage units), and thus be regulated much more easily than other renewable electricity. According to the interviewees, current regulations and subsidy systems do not promote this system service provider function in the Netherlands, while there is an attempt to change this with a flexibility premium in Germany. However, this requires specific technological adaptations and the normal route of running a CHP unit continuously is currently more attractive for most biogas producers.[4]

[4] The flexibility premium has been introduced in the 2012 update of the German subsidy scheme Erneuerbare-Energien-Gesetz (EEG). In 2014, about 20% (ca. 800MW of 3905MW) of installed capacity of biogas production was able to provide electricity flexibly [160]. In the 2014 update of the EEG, the stimulation of flexible provision was increased further for new installations: only half of the installed capacity is subsidised and this is combined with an additional supplement for flexible provision through use of gas storage [311].

Interviewees also argued that another role for biogas in the energy mix could be to replace fossil energy that is difficult to replace with other renewable energies. Most often mentioned are energy sources for sectors that cannot switch easily to electric energy, such as fuels for shipping, road transport and air transport, and the production of industrial heat. Next to the use of green gas, upgrading biogas to bio-LNG (liquid natural gas) could provide an opportunity to replace fossil fuels in these sectors. One interviewee observed that green gas, just like natural gas, is often used for heat production, while it could substitute transportation fuels that are far more difficult to make and more valuable.

Most interviewees expected that in the future, biogas production will diversify into producing multiple products. Technology development is focussing on using by-products and creating additional products (see the following section). The whole production chain is considered, from pre-treatment of biomass to post-treatment of digestate. Potential products named are proteins, fibres, lignin, nitrate, phosphate, potassium, rare earth elements, carbon dioxide and water. These additional products could make the business model around biogas more stable by adding new customers, while energy remains as one of the products or even becomes a by-product.

According to some interviewees additional advantages are win-win situations, where the products mitigate currently existing problems, for example replacing artificial nitrate production requiring high energy inputs, or recirculating phosphate, which is less and less readily available in concentrated form and as a consequence turning into a scarce resource worldwide. They also propose that biogas installations can form a processing step, separating biomass into its components. While some parts could be separated up front, others remain in a more concentrated form in the residues after organic components have been removed during the digestion, making them a good input for further processing. However, some interviewees say that it is still unclear how a good balance between products can be achieved. Biogas energy yields could decrease if the focus shifts to multiple products, but the traditional focus on one product could also inhibit the optimisation of the process towards multiple products.

Discussion: Biogas as by-product for specific energy applications

The choice between biogas or green gas production described by the interviewees is mainly related to renewable energy production and the integration of bioenergy in the current energy system. Generally, this choice should aim at using biogas or green gas as efficiently as possible, taking into consideration aspects such as the regional situation, the efficiency of CHP *vs.* green gas in household heating installations, and the potential for short-term storage of heat. Both biogas and green gas producers are adapting to the current possibilities of the energy market. In December 2015 the Dutch Ministry of Finance published a vision paper on biomass in the Netherlands by the year 2030, in which it confirms the opinion of some interviewees that bioenergy is especially interesting for transportation fuels and industrial applications [170]. Specific energy applications, such as transportation fuels, industrial applications and functioning as a system service provider, could be the most interesting future routes for biogas production according to the Ministry. The broader option of producing multiple (energy and non-energy) products and viewing biogas for energy as only one of the products or even a by-product is closely related to the bioeconomy development, where different concepts such as biorefinery and cascading strive for the creation of multiple products from biomass resources. This could offer new possibilities for the biogas sector. Expanding biomass use from energy production to other products has been described as promising for the enhancement of energetic and economic efficiency, but also challenging regarding the definition of efficient biomass use [181]. Combinations of biogas for energy with other bioeconomy applications, though technically interesting, may be difficult at this stage because they further complicate both the production process and the business case, thereby increasing risks.

### 3.5.3 Technology

Technology for biogas production is perceived by most interviewees as still under development but getting more and more robust and efficient. Development now often focuses on using more difficult, heterogeneous feedstock, making use of by-products such as $CO_2$, and extracting components from digestate, such as nitrogen and phosphate compounds. Interviewees identified the dependence of the business case around biogas production on subsidies as one of the reasons for this development. Traditionally, biogas producers have to pay for both the input (the co-substrate) and the output (treatment of digestate). The price for the produced biogas is determined by current subsidies, so it is the input and output side where the business case can be influenced, creating higher incomes by reducing the costs for resources and residues. This stimulates the search for cheaper resources and better use of by-products and digestate. The more traditional biogas digester may then transform into a wider processing route, where biogas itself is only one of the products. Interviewees expect the most promising processing route to be a useful application of biogenic waste streams, i.e. where biogas provides the energy for the process and some extra, and components in the effluent are extracted, concentrated or purified. They expect that biogas can serve as a basis for further development of technology for the bioeconomy, increasing the efficiency of energy production and developing methods to extract different components, making different or multiple products. In the estimation of some interviewees, the biogas sector can still learn from other sectors, especially regarding processing technologies and equipment. Examples named are the food and feed industry (processing of straw to make it better digestible, drying techniques), the chemical industry, and biotechnology.

An issue that requires further consideration according to some interviewees is the logistic organisation of biogas technology. Decisions regarding location for the biogas installation itself (transport distance biomass), but also nutrient recovery or upgrading installations (decentralised or centralised), as well as energy production (location CHP or feed-in into the gas grid), influence the overall business case.

#### Discussion: from energy production to broader biomass processing

Focus in biogas technology appears to be moving away from mainly increasing yields within the digester itself to tweaking the front and rear end of the production chain. This also widens the focus from one product, biogas, to multiple potential products and a more diverse business case. With regard to the renewable energy and bioeconomy policy domains, this development could represent a shift away from pure energy production towards broader biomass processing routes with multiple outputs, similar to the technologies envisioned in a bioeconomy. The bioeconomy may offer chances to increase knowledge transfer between sectors, since it is envisioned that fossil-based products in various sectors are replaced by biomass and concepts such as cascading use of biomass and biorefineries enable but also require collaboration across sectors. Logistic decisions could be influenced by the development of both the renewable energy sector and the bioeconomy. Especially the development of biorefineries could determine the level of centralisation of processing steps. Biogas production may become an integral part of a biorefinery.

### 3.5.4 Financing and regulations

Interviewees described financing (both through subsidies and investors) and regulations as main barriers for the further development of biogas production both as renewable energy and in the context of a bioeconomy. Some criticise the fact that subsidies are mainly stimulating the use of biogas for electricity production. They claim that this focus on specific technologies leads to very uniform biogas installations with little room for experimentation and innovation. Developments towards more diverse products or other energy products are scarcely stimulated and thus unattractive. Furthermore, the financial push of using biomass for energy indirectly hampers other applications or cascading, since only energy applications can receive a subsidy. For example, methane based on green gas could serve as an input in the chemical industry, but is rarely applied. In Germany, subsidy is not granted for methane production itself, but only for the electricity output at the CHP unit.

A crucial difficulty in the realisation of biogas production for many interviewees is the financing of projects. Financing from banks or public funds is connected to strict requirements, especially in the Netherlands. For example, it is required that biogas producers show that they will receive subsidy for renewable energy production and have established long-term user agreements for the produced energy and long-term biomass supply contracts. Especially the latter is very hard to acquire for biogas producers that do not produce their own co-substrate. Intermediaries, trading biomass from various sources, can offer security of supply, but orient their prices on the subsidies to be received, increasing their own profit margin while reducing that of the biogas producers and thus increasing the risk of investments. When residual biomass resources are used, an additional difficulty is that the amount of residues depends on the original product stream, not the demand of the biogas installation.

Financing of innovative projects is perceived to be especially difficult. Technically, higher yields of biogas may be achievable, but new technologies require higher investments, which constitute a risk few investors are willing to take. If anything else but energy is produced, subsidies are not granted and often that rules out financing. The security of demand is difficult to prove for additional products next to energy, since they rely upon new or developing markets.

Interviewees identified several bureaucratic obstacles that in their perception hamper biogas development. First of all, when setting up a biogas project, companies have to hand in a variety of permit applications, including environmental reporting and public consultation procedures. The process is perceived to be overly complicated, time consuming and difficult for small companies. Decisions on applications regularly took half a year or even a year in the Netherlands.

Regulations regarding input and output streams further complicate matters. At the moment, it is not allowed to use digestate as a replacement for artificial fertilisers in the Netherlands. This is described as a big constraint for biogas production in the Netherlands, because the treatment or export of digestate has to be paid for. Furthermore, regulations regarding resources that are allowed to be used as co-substrates in biogas installations differ across the EU. In some countries, a certain biomass resource may be allowed, while it is not in another and the other way around. As a consequence, biomass distributers profit from transporting biomass across the EU, selling it where it is allowed. Interviewees argue that this decreases the efficiency of biogas production and makes it more complicated to use biomass locally or regionally.

Different EU countries use different systems of pricing, subsidies, and certifications. Additionally, they have different gas quality regulations. This can be difficult for international trade, for example in green gas. Opinions regarding trade in green gas differed among the interviewees. One interviewee argued that systems dealing with the ‘green value’ of gas could provide a good opportunity for national and international trade. However, the prices of certificates are not high enough and an offer by a third party to buy a certificate is insufficient to get financing from a bank. Other interviewees argued that certificate schemes can carry the risk of quickly losing value, as has been experienced with $CO_2$ certificates in the past. Certification schemes are often not compatible internationally and according to some would have to be based on a measurable, technical value, not only on guarantees of origin or similar paper trails.

Two main differences between Germany and the Netherlands became apparent in the interviews. First of all, in the Netherlands, many data are more freely available than in Germany, for example geographical data, information about gas networks, and locations of users or companies. Secondly, the main focus and the level of consistency in policies regarding biogas production differed in both countries. In Germany, the focus is very much on renewable energy production as part of the 'Energiewende' (energy transition). To promote this, subsidies were granted to specific technological solutions, mainly the application of biogas in CHP units, and specific groups of people, mainly farmers. This has increased the number of biogas installations, but has also resulted in a very uniform landscape of biogas production. In the Netherlands, less subsidies were granted and they were a lot less stable, leading to more experimentation and more diverse solutions, but also a lower implementation of biogas technology.

### Discussion: subsidies vs. innovative solutions

The experiences shared by the interviewees suggest that a subsidy focus on renewable electricity has hampered the development and production of other forms of renewable energy by means of biogas, but also the production of alternative or additional products and technologies. This is neither favourable for bioeconomy policy goals, nor does it promote the position of bioenergy in the renewable energy mix. With financing being strictly linked to renewable energy subsidies, which in turn are largely based on electricity production, innovative solutions in the production of biogas and other products, which may be technically feasible and attractive to improve the overall business case, become difficult to realise. While developments in the sector are focusing on integration in the bioeconomy, subsidies for biogas production are currently only granted in the renewable energy policy domain. Chemical production from biogas or green gas is not subsidised, which currently makes it less attractive than energy production. Current energy policies aim for an increased production of renewable energy, and especially electricity. The focus of subsidy schemes on electricity production from biogas or green gas is therefore logical, but does not necessarily promote an efficient use of resources or optimal business cases. Instead of efficient resource use and creation of multiple products, the focus of subsidies lies on optimal energy production only, because it is motivated solely by energy considerations. This focus does not go well with the vision in the bioeconomy domain, where different and more drivers are at play and energy is only a sideshow. Innovations in the sectors towards a better contribution to both policy goals are thus hampered by the diverging focus of the two policy domains and a lack of incentives in the bioeconomy domain. To increase overall benefit, policies in the two domains would have to be aligned better and aimed at optimal use of biomass resources for multiple goals.



### 3.5.5 Overview of results and general discussion

The results of our empirical analysis of the current practices of biogas production and its position between policy domains are summarised in Figure 3.3 and Table 3.2. Figure 3.3 shows the most important technical links between biogas and the two policy domains. Important opportunities and constraints to contribute to the two policy goals resulting from the in-between position of biogas are summarised in Table 3.2.

Table 3.2: Opportunities and constraints of biogas between policy domains.

| Topic | Discussion Point |
|---|---|
| Resources | Change of perspective: from using the best feedstock for energy production to using all biomass resources optimally |
| | Better use of residual biomass: combining efficient processing of organic waste streams with creating added value through extraction of valuable components and production of renewable energy |
| | Starting today: using all available biomass for currently feasible processes, thereby mobilising biomass and creating stepping stones towards a more integrated use of biomass resources |
| Products | Context: adapting choice between biogas and green gas to the local and regional landscape |
| | Function in energy system: from inflexible renewable energy source to system service provider, using biogas where it offers advantages over other renewables, e.g. profiting from flexibility and application for difficult energy carriers |
| | Multiple products: no longer just energy but multiple products, integrating in bioeconomy concepts like biorefinery |
| Technology | Shifting focus: away from only increasing biogas yields towards tweaking the front and rear of the production chain |
| | More diversity: more products and more divers business cases. Fermentation as processing step, creating enabling technologies for a bioeconomy |
| | Unclear logistics: appropriate scales, logistics and integration in landscapes require more attention |
| Financing & Regulations | Financing related to subsidies: aiming at specific technologies or products leaves little room for experimentation and innovation |
| | Level playing field: subsidies favour energy production over new or additional products and inflexible financing possibilities hamper innovative business cases |
| | Complications: bureaucratic obstacles and international differences counteract expansion and innovation |

In the renewable energy domain, biogas is mainly appreciated as a versatile energy source that can be used to produce electricity, (industrial) heat or transportation fuels, and that can be stored, transported and used when and where needed. In the bioeconomy domain, it is included as a way to use low-value biomass, at the end of cascades, and as a by-product. In current practice opportunities are explored to link biogas production to the bioeconomy through extraction of components and production of by-products (Figure 3.3).

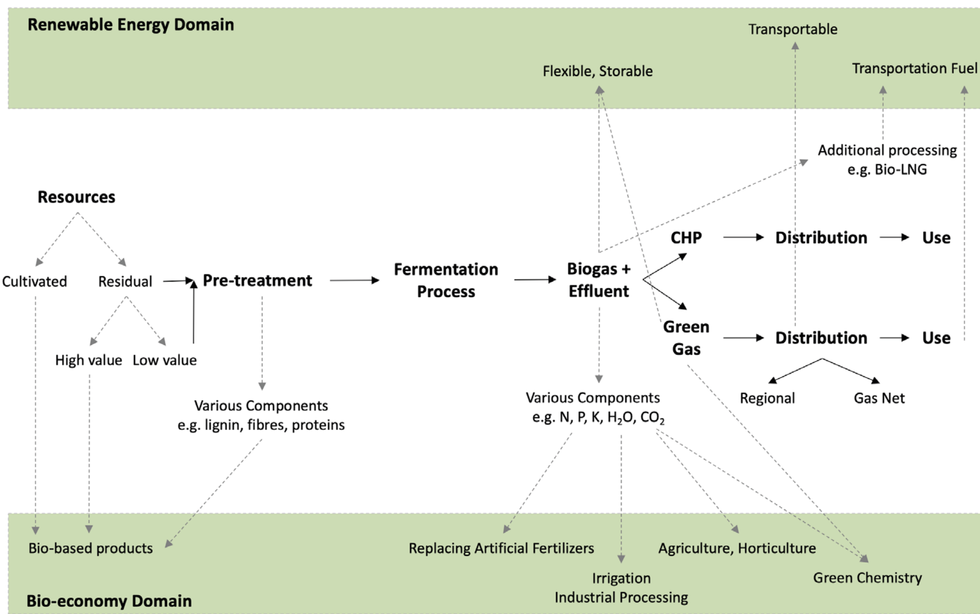


Figure 3.3 Schematic representation of potential technical links of biogas with the renewable energy and bioeconomy policy domains.

One of the biggest challenges in the transition to a bioeconomy is to prioritise between different applications. Concepts such as cascading and biorefineries aim at producing multiple products and using resources efficiently, as discussed by Bruins and Sanders (2012) and Vaneeckhaute et al. [138]. Our study shows, however, that current practice is still dominated by a competition for resources used for energy production only. Furthermore, many technologies still rely on cultivated (first generation), high quality and homogenous biomass, while policies aim at more diverse feedstock [169,170]. Our study revealed that in the biogas sector it is expected that higher-value applications in the bioeconomy will increasingly compete for biomass and will be able to pay higher prices. As a consequence, biomass owners tend to be cautious with long-term commitments of biomass supply for fixed prices, because they expect to profit from the higher purchasing power of bio-based producers in the future. However, bio-based products not only compete with bioenergy over resources, they also compete with fossil-based products via product prices. While they try to close in on the cost price of their fossil benchmarks, their business case is not necessarily stronger than that of biogas, especially because they do not receive subsidies. The expectation that in the future biomass will increase in value because different players are able to pay more for it, is thus not necessarily accurate. This is especially true for low-value, heterogeneous biomass, such as many residual biomass streams, that require intensive pre-treatment. The feasibility of all business cases is furthermore dependent on the development of oil prices.

The subsidies currently granted in the energy domain are instruments designed to bridge the gap between the market price for energy and the cost of renewable energy production. Arguably, this gap exists only because the external (societal) costs of non-renewable energy production are not reflected in the price of energy. The costs of these externalities (like the production of GHG and radioactive waste) are borne by society. As long as these costs are not reflected in the price of energy, renewable energy production will probably require subsidies. However, these subsidies make other uses of biomass, which are not subsidised, less attractive. In the light of multiple goals for biomass use in both the renewable energy and the bioeconomy domain, the competitive position of biomass-based products in comparison with fossil-based products is an important aspect limiting the potential to achieve the goals in both policy domains.

The idea to move away from high value crops to residual biomass is regularly discussed as a possibility to address controversies and land-use issues [33,36]. However, a narrow focus on the sustainability challenges of high value crops, such as the 'food *vs.* fuel' debate, and a focus on biomass supply hamper a holistic view on residual biomass as alternative biomass source [36]. Our study revealed that in current practice there is a focus on using all biomass resources optimally and combining processing of organic waste with energy production (Table 3.2). But it has to be taken into account that residual biomass is seldom without function, which is lost when it is re-directed to biogas production [33]. The impacts of using residual biomass should be addressed from a broad and more inclusive sustainability perspective, including ecological and economic impacts. More generally, in the future it will be important to ensure a sustainable supply of biomass under increasing demand for biomass from different sectors, which may be less strictly regulated than the energy sector.

Logistic aspects of biogas production, such as an appropriate scale of installations, the level of (de)centralisation and integration in landscapes pose uncertainties in current biogas practice and require more attention (Table 3.2). Regarding the spatial context of biogas installations issues of importance are, for example, local availability of resources (manure and co-substrate, e.g. on farms), vicinity of users of the produced heat, and connectivity to infrastructure (transport networks, gas and electricity grid access). On the one hand, de-centralised biogas production offers the advantage of being adaptable to local circumstances and using locally available biomass to avoid transport [182]. Vicinity of potential users of by-products of biogas production may, for example, increase chances to realise multi-purpose applications of biomass [183]. On the other hand, upgrading biogas to green gas is very expensive and far more feasible on a centralised scale than for individual installations. In between these extremes, regional networks of local initiatives can help biogas producers to profit from e.g. multiple biomass suppliers or multiple heat users, making both supply and demand more robust [183]. Embedding biogas production in a local situation does, however, rely heavily on social capital [184].

It should be noted that this paper was based on interviews with project leaders of a large European project focused on green gas, which imposes some limitations on our findings, but allowed us to receive practical and personal information. Interviews provide indirect information, filtered through the views of the interviewee [55], which is further influenced by the type of questions in this study, relating not only to objective project outcomes, but also to experiences and perceptions on the potential of biogas in the realm of current and future policy domains. The answers of our interviewees were influenced by their background and the subprojects they participated in. This may have triggered them to address certain opportunities and constraints while neglecting others. In this sense, the interviews are not necessarily representative for the experience of all relevant stakeholders in the biogas sector. However, any effects of subjectivity were minimised through the thematic analysis of the interviews, in which we collated themes expressed by the interviewees and discussed them in the context of the policy domains to provide generalised insights. We think that the practical and personal nature of data in this study provided valuable in-depth information on the actual challenges in current biogas practice, partly confirming but also extending and highlighting the information from policy and research (Sections 3.2 and 3.3).

## 3.6 Conclusion, policy implications and future research

The purpose of this paper was to examine the relationship of current biogas practices with the renewable energy and bioeconomy policy domains and identify how biogas can contribute to both policy goals. The exploration of the position of biogas within the policy domains showed that biogas can play an interesting, dual role in both of them. Our empirical study revealed some developments in current biogas practice that offer opportunities for an improved contribution of biogas to both policy domains. Innovation efforts appear to be focused mainly on a better integration in the bioeconomy. In the renewable energy domain, upgrading to green gas has the potential to make biogas the envisioned system service provider, but faces technical, financial, and logistical difficulties. Technical developments mostly focus on using lower value, more difficult resources and adapting the processing technology towards producing multiple products. These developments fit well with bioeconomy policies. Our study also revealed several constraints for a contribution of biogas to both policy goals. The advantage of biogas as versatile system service provider in the renewable energy domain is underused in current practice and not stimulated effectively. Innovations towards multiple products for a bioeconomy are hampered by subsidy schemes, regulations and bureaucracy. And the use of alternative, residual biomass resources is impeded by limited financing possibilities.

Biogas can provide a valuable contribution to both policy domains, but only if the current focus on energy is diversified. In the long run, it is probable that biogas will no longer be a solitary main product, but rather one of many products created in intricate biomass processing. It can, however, remain a useful processing step and a way to make use of otherwise unusable biogenic residues and create added value during necessary waste treatment. Future research should focus on defining the most efficient use of all biomass resources and developing technologies to extract as many valuable components as possible. In the meantime, biogas production is a technology that is already available and can be applied to use biomass efficiently right now. There are various links to new and existing technologies in both the renewable energy and the bioeconomy sector, that can be used and developed further. The use of biomass to produce biogas right now can furthermore provide an incentive for biomass owners to harvest and use or sell their biomass, thus increasing the availability of biomass. Biogas can thus serve as a stepping stone in the transition towards a bioeconomy: biomass can be used for feasible applications now, while also enabling the development of new technologies for improved efficiency in the future.

Energy transitions have been described to be changing in character, with different drivers than in the past and the potential to accelerate, drawing on synergies between multiple domains [185]. Biogas has the potential to contribute to such synergies and as a system service provider can also serve as a stepping stone in the transition towards a renewable energy future [cf. 186]. This underlines the dual, but also time-dependent role of biogas in two transitions.

The diverging goals of both domains currently hinder the development of innovative connections between them, even though current practice already offers many opportunities for smart combinations. Hurdles such as overly complicated bureaucracy and rigid financing schemes should be lowered and subsidy schemes should allow for alternative business cases, including different products. Political insecurity and ups and downs in policy schemes have been a major hurdle for development in the past. In the future, joint goals, clear priorities and fair policy schemes should be designed to overcome inefficiency in the sector. Policy makers should jointly aim at optimal use of biomass resources for multiple goals, to increase the overall benefit. To maximise the contribution to both policy goals, policies must be more balanced to enable all valuable functions of biogas. Policies should aim at improving the competitive position of biomass-based products over fossil-based products and optimising the use of biomass resources, rather than inciting competition between the different biomass applications. This aligns with the conclusion of Silveira and Johnson [187], stressing the importance of coordinating bioenergy policies across sectors and considering biomass not only in the energy domain, but taking advantage of complementary uses of biomass in different sectors.

The project under investigation in this paper involved two European countries, but similar developments might also be observed in other countries with policies for both renewable energy and a bioeconomy. Future policy development could benefit from research about the policy coherence in other countries and comparison of opportunities and constraints experienced there. Lessons can be learned both from countries where the policy coherence might be greater and countries where bioeconomy policies are more fragmented, such as Canada, where competing visions were detected even within one domain [188]. This paper, based on interviews with a selection of stakeholders, provides insights into opportunities and constraints for biogas to contribute to both domains. Further research to understand visions of various stakeholders can be a valuable instrument to establish aligned goals for the renewable energy and bioeconomy policy domains.

Biogas is not the only issue that falls under two policy domains. The concept of coherence between policy domains has been addressed in general by May et al. [189], concluding that increased policy coherence can improve implementation success and policy acceptance. They found that focussed attention for specific issues, supportive institutional structures, and involvement of interest groups can foster greater policy coherence. Examples of other issues falling under two policy domains are the consideration of forestry in climate change policies [190] and the changing perspective on water management, where the technical water management and spatial planning policies meet [191]. Future policy development in the bioeconomy and renewable energy domains could benefit from research into lessons learned from other sectors where policy domains intersect.

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# Chapter 4

## Residual biomass –
## A silver bullet to ensure a sustainable bioeconomy?

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## Abstract

The transition to a bioeconomy is generally considered as a step towards increased sustainability. However, increased biomass production can have several negative impacts and as a consequence, many cultivated biomass resources are unsustainable, thereby counteracting the sustainability objective of the bioeconomy. One proposed alternative is the use of residual biomass: biomass that is not cultivated for the use in a bioeconomy directly but is a waste product of other processes. Since residual biomass is not produced on agricultural land it appears to be a silver bullet for sustainable biomass supply. But is that really the case? This paper discusses conditions that determine whether the use of residual biomass is indeed sustainable. Based on an extensive literature review we conclude that residual biomass is not a silver bullet but can contribute to sustainability under certain conditions. Most importantly, the consequences for sustainability of changing current use have to be evaluated. Residual biomass is only seldom purely waste and regularly fulfils other functions, such as maintaining soil quality or providing habitats. The benefits of extracting residual biomass for new applications, thus causing a resource use change (RUC), have to outweigh the loss of their former function. Furthermore, not all residual biomass uses contribute to sustainability equally. Applications should be optimised to achieve various sustainability goals. Advances can be achieved through adapting technologies and logistics and increasing synergies between biomass-processing sectors.

## 4.1 Introduction

Global challenges, such as reducing human dependence on fossil resources and emissions of greenhouse gases (GHG) causing human-induced climate change, are drivers for the development of a bioeconomy, in which biomass replaces fossil resources in various supply chains. The importance of sustainability in the development of a bioeconomy is broadly recognised [167]. However, it is heavily debated whether an increased use of biomass resources contributes to a more sustainable situation. If biomass demands cannot be met in a sustainable way, the sustainability objective of the bioeconomy cannot be reached. Especially negative effects on GHG emissions and ecosystems of land-use change in favour of increased biomass production are noted [e.g. 14]. One strategy that is often proposed by researchers and policy makers to avoid negative impacts of increased production is the use of residual biomass. Since residual biomass does not have to be produced on agricultural land, the initial assumption is that through avoiding land-use change it is a sustainable alternative to biomass crops. Furthermore, it is generally assumed to be cheaper than cultivated biomass. All in all, residual biomass use appears to be an effortless, immediate and fail-safe solution to a complex problem for sustainable biomass supply. But can residual biomass really be the 'silver bullet' enabling a sustainable bioeconomy?

The goal of this paper is to discuss conditions that determine whether use residual biomass contributes to sustainability. First, biomass supply and demand and their consequences on sustainability are discussed, reflecting shortly on the historical perspective of biomass use. Subsequently, Section 4.3 reflects on proposed strategies to mitigate these consequences, focusing on residual biomass. One important aspect of residual biomass use, called resource use change, is highlighted in Section 4.4. Section 4.5 discusses how different applications of residual biomass are related to sustainability. Reflecting on currently handled sustainability criteria the paper finally elaborates on conditions for the sustainable use of residual biomass.

## 4.2 Biomass supply and demand in the past and present: consequences for sustainability

Before the Industrial Revolution, biomass-based energy and other renewable energy sources dominated energy supplies [192–194]. These were mostly replaced by fossil energy carriers during and after the Industrial Revolution in Europe, initially dominated by burning coal instead of wood [194]. Biomass applications as materials have undergone similar developments around a century later. Chemical research was initially driven by the potential to convert biomass into fuels and chemical products, and until the beginning of the 20$^{th}$ century many chemical materials were based on biomass. Petroleum-based products later gradually displaced most of these biomass-based products with the rise of the petrochemical industry in the 1950s [195–198].

For various reasons, efforts are currently being made to reduce or even abandon our consumption of fossil resources. These developments have stimulated the expansion of applications and modern technologies for biomass use. Contemporary applications accompany traditional biomass uses and include both new sources of energy and materials, for example biofuels and bioplastics. The new opportunities to replace fossil resources with biomass have contributed to the vision of the so-called bioeconomy. Where in the past biomass inputs for non-food applications were gradually exchanged for fossil resources, it is now attempted to reverse this development. The bioeconomy is thus in fact a *renaissance* of biomass use.

However, achieving a switch back to biomass-based production brings with it a fundamental problem. Before the Industrial Revolution, biomass enabled, but also constrained economic growth: the available energy was limited to the annual regrowth [194]. Before this limitation was overcome by the use of fossil resources, various countries around the world had already experienced shortages of biomass supply to fulfil their growing demands for energy [199]. Overexploitation of resources created problems and triggered the switch to the use of fossil resources. In Britain, fossil material use soon exceeded what could have been supplied by sustainable biomass exploitation from woods, pastures or cropland [199]. Today, our energy demands are higher than ever and still predicted to rise. The fact that biomass resources could not supply sufficient sustainable energy before the Industrial Revolution provides an daunting perspective on current efforts to engage in a transition *back* to an economy driven by biomass. Paradoxically, the availability of fossil resources seemed practically unlimited during the Industrial Revolution, in contrast to ‘fresh’ biomass, though fresh biomass regrows fast in comparison with virtually non-renewable fossil resources. Today we face the finite nature of fossil resources and the negative impacts of their exploitation and turn back to renewable, fresh biomass.

If renewable resources are to supply enough commodities to replace human consumption of fossil-based goods, this will have serious consequences for the demand for raw materials [136]. Improved agricultural techniques, modern processing technologies, and more efficient resource use may help to tackle this problem. However, land availability is considered a limiting factor for biomass supply for a bioeconomy [58,71,81,116,200]. Global population growth and higher per capita consumption create a double rising pressure on raw materials and natural resources. Even with modern technologies and highly increased efficiency, the question remains whether humankind can fulfil its demands for resources in a sustainable way.

Rising demands for biomass resources can lead to undesired consequences. If the demands for material and energy applications were to be met with cultivated biomass while at the same time producing more food for a growing and increasingly prosperous world population, agricultural production would have to increase strongly. This would require either increased yields on the same area of land currently used for agricultural production, or an expansion of cultivated land.

A proposed alternative for biomass production is the cultivation of aquatic biomass, mainly algae, making use of the vast areas of the globe covered with water, thus avoiding competition for land areas. Cultivation and processing techniques have been under development for years and are currently further advanced, aiming for example at the production of biofuels [23–25]. Nevertheless, use of land-based biomass resources is currently dominant and therefore chosen as focus in this paper.

Criticism of biofuels, and bioenergy in general, often refers to their effectiveness in reducing GHG emissions relative to fossil fuels. Proponents of bioenergy argue that the carbon uptake by plants makes biomass a carbon neutral resource, in contrast to fossil resources. Use of biomass for energy requires several processing steps consuming energy and materials, but the total sum is argued to be favourable in comparison with fossil fuels, due to the initial carbon uptake. However, changes in land-use or expansion of land-use can cause emissions of carbon that counteract the benefit of carbon uptake by plants. In 2008, Searchinger et al. published a study analysing the effects of direct and indirect land-use changes on the overall GHG emissions of biofuel production in the USA. Since then, land-use change (LUC), and especially indirect land-use change (iLUC), dominate debates on the carbon footprint of bioenergy. Land-use change can be defined as any change of one type of land-use to another [15]. Biomass production can cause GHG emissions through land-use change directly or indirectly. Direct LUC causes emissions if land harbouring carbon-rich ecosystems such as forests is converted specifically for the purpose of biomass production on that same land. GHG emissions from iLUC occur if land formerly used for the production of other feedstock (e.g. food production) is used for the production of biomass for energy or materials instead. As a consequence, carbon-rich land elsewhere is converted to make up for the feedstock no longer grown on the original land [12,14–16].

Both types of land-use change can cause significant GHG emissions during and following the initial land-use conversion. GHGs are emitted rapidly through slash and burn of natural land cover and microbial decomposition of plants, and over a prolonged period of time through the decay of roots [18]. In many cases the time before the initial emissions of carbon are offset by carbon savings of biofuels (carbon payback time) is long [18,19,21], which is problematic for the mitigation of climate change in the short term.

Land-use change furthermore has adverse effects additional to GHG emissions. The conversion of pristine ecosystems such as forests and grasslands, but also of diverse agroforestry systems, causes habitat destruction and may lead to biodiversity losses [12,18,84].

While land-use change effects have mostly been described for biofuels, they are also reflected in the scientific debate regarding the broader bioeconomy. Competition for land, competition for resources, and the uncertainty of emission reductions are the three most described problems regarding the contribution of a bioeconomy to sustainability [167].

In summary, land-use changes as a consequence of the renaissance of biomass for the production of materials and energy can lead to negative effects on carbon emissions, biodiversity, and food production, which counteract the sustainability objective of a bioeconomy.



## 4.3 Advantages and disadvantages of residual biomass use

To avoid the negative effects associated with land-use change two strategies are often suggested: the use of degraded or marginal land for the production of biomass, and the use of residual biomass for the production of energy and materials [e.g. 16, 18, 21, 84, 87, 91, 96, 133, 139]. While the advantages and disadvantages of marginal land in comparison to productive land have been discussed by some [e.g. 21,120,140], not much is known about the relationship between residual biomass and sustainability. Therefore, this paper focuses on the strategy of using residual biomass.

Generally, two types of biomass resources for contemporary applications can be distinguished: cultivated biomass and residual biomass (see Figure 4.1). While Hoogwijk [32] distinguishes between energy crops and biomass residues, the term “cultivated biomass” is chosen here to include all biomass produced specifically for non-food purposes. Next to energy crops, this includes for example biomass produced in forests or cultivated algae. Residual biomass is biomass that not produced for its use as for example energy source directly but is a waste product of other processes. It is also referred to as “biomass residues” or “waste biomass”. Hoogwijk [32] distinguishes four types of residual biomass resources: agricultural residues, forest residues (incl. material processing residues), animal manure and organic wastes (e.g. waste wood of municipal solid waste). Here, the term “landscape residues” instead of forest residues is chosen to include biomass released during landscape maintenance activities in various types of landscapes. Next to forests, this includes half-natural landscapes influenced by humans, for example pastures or floodplains, but also roadside vegetation (see Figure 4.1).

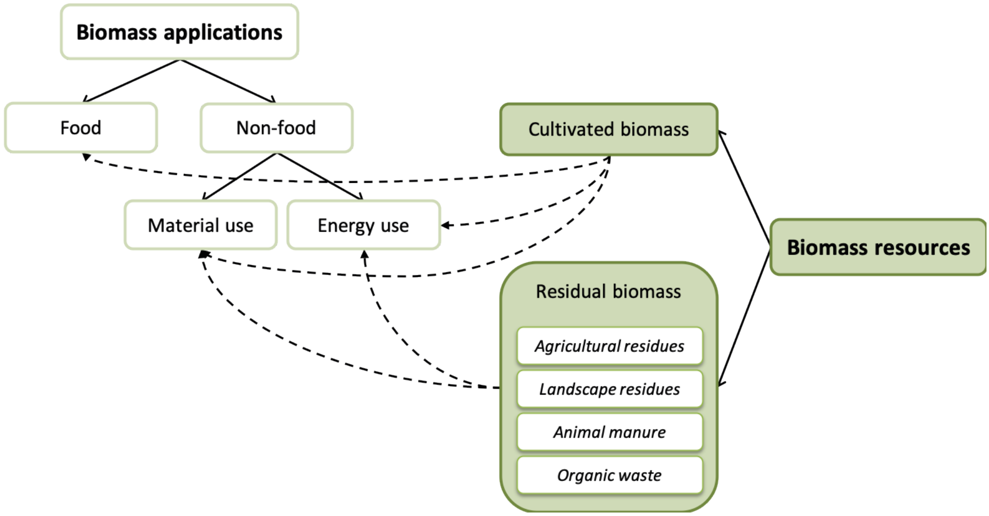


Figure 4.1 Contemporary biomass applications and resources.

Using residual biomass as input for new production chains offers several sustainability advantages (Table 4.1). First, no additional land is required to produce biomass, which foregoes land-use change. Second, applying otherwise unused material as input for new production chains reduces waste. Third, biomass that is left to rot may emit GHGs. Using this biomass will in the end still lead to GHG emissions, but by re-using this biomass other energy sources or materials can be substituted, reducing overall emissions. Finally, using residues increases the overall efficiency of resource use and can contribute to a 'circular' resource use or a no-waste society, concepts closely related to sustainability.

However, residual biomass also poses a number of challenges (Table 4.1). Quantitative potentials of biomass supply from residual biomass are limited and much smaller than potentials from crops [32]. It is therefore all the more important to use these streams in a sustainable way. It is questionable if potentials from residual biomass are high enough to fulfil demands in Europe, even in combination with biomass production on marginal land and increased efficiency.

Another challenge is the spatial availability and accessibility of residual biomass. Since the residues are by-products of other processes, they are initially situated in different, possibly widespread or difficult to reach locations. While cultivation of biomass is optimised for harvest and preservation of desired qualities, residues are not necessarily collected and stored appropriately. Collection and transportation for further use result in costs and emissions. Furthermore, processing, external impact, storage and transport can all lead to quality losses. These effects strongly influence the efficiency and sustainability of using residual biomass for applications within the bioeconomy. Ideally, processes would have to be optimised for reuse of waste streams by, for example, collecting residues on site and storing them appropriately or directly processing them further. Essentially, residues should then be treated as by-products or secondary products instead of waste. It could be advantageous to adapt technologies to be efficient on a small scale to avoid long distance transport and storage, which is associated with problems of odours and volatile organic compounds [84].



The quality and characteristics of residual biomass pose an additional challenge. Coming from a variety of sources, residues are far more heterogenic than cultivated biomass sources, especially waste streams like organic waste in urban areas [39]. Many studies argue that to achieve an efficient use of resources all components of any biomass resource should be used [41,45,58,78,79,85,91,92,140,167]. This may refer to the use of all parts of crops, including parts that would otherwise be residues, or to specific components of plants, such as sugars, cellulose, or lignin. To use residual biomass resources efficiently, technology has to be adapted to cope with the variety and heterogeneity of different types of biomass and with all the different components.

Carbon payback times of substituting fossil resources with residual biomass differ between regional circumstances. Lamers and Junginger [21]compared three different scenarios of substituting different fossil energy carriers with forest residues, showing that carbon payback times differ between 0 and 44 years. Thus, while some options offer almost immediate carbon benefits, the mitigation potential is not only determined by the feedstock and not all applications of residual biomass are equally successful. Case specific assessment is thus of great importance.

Finally, novel applications may disrupt existing functions of residual biomass. This aspect is rarely addressed when new applications of residual biomass are considered. Therefore, the next section elaborates on this challenge of a change in resource use.

Table 4.1 Expected advantages and challenges of residual biomass use.

| Expected sustainability advantages | Challenges |
|---|---|
| No additional land required | Availability and accessibility |
| Waste reduction | Quality and components |
| GHG emission reduction | Carbon payback times dependent on regional circumstances |
| Circular resource use | Impact of resource use change (RUC) |

## 4.4 Resource use change

When residual biomass is considered as waste, using it for a new purpose may appear to offer only advantages. However, even though residual biomass is not produced directly for a specific application, in many cases it does fulfil a function nonetheless. Residues are seldom unused waste streams and even abandoned or treated waste can provide functions. If these resources are then used for new applications, this has consequences on the former function. I refer to this phenomenon as resource use change (RUC) in this paper, to demonstrate the resemblance with LUC. Where (i)LUC represents a change to current land-use, RUC refers to new uses of resources that are provided by this current land-use. These changes may or may not lead to LUC in consequence.

Table 4.2 shows several functions of residual biomass in different situations, illustrating them with examples, and referring to possible consequences of a RUC. Three current situations are distinguished. First, residual biomass can be extracted to serve as input in other supply chains. Second, biomass that is left behind – for example in the field or in an ecosystem – often fulfils a function. It may serve to sustain soil quality or provide ecosystem services. Soil organic matter is an important factor in both ecosystems and agricultural production. Biomass left behind is decomposed and provides important nutrients for renewed growth [201,202]. Both fine and coarse debris provide habitats for various species and are therefore important for ecosystem health and biodiversity [203–206]. Third, biomass that is not used and enters waste treatment can still fulfil a function. Biomass residues such as organic or green waste are often treated and provide compost or energy.

Table 4.2 Functions of residual biomass and consequences of RUC.

| | Function | Examples | Possible consequences RUC |
|---|---|---|---|
| **Extraction** | Input supply chains | • Wood residues for pallets<br>• Wood residues for composite materials<br>• Straw for fodder | • Disturbance of supply chains<br>• Increase of market prices<br>• Replacement with cultivated biomass |
| **Left behind** | Sustaining soil quality | Agricultural residues or straw mixed in soil | Soil degradation |
| | Ecosystem services | • Provision of food, nutrients or habitats<br>• Input for trophic interactions<br>• Enabling biodiversity | • Loss of ecosystem services<br>• Disturbance of ecosystem functioning<br>• Biodiversity loss |
| **Waste Treatment** | Provision of energy | Energy from waste incineration | Reduced energy provision; increased use of fossil energy |
| | Provision of compost | Compost for soil organic matter re-nourishment | Reduced availability of compost; increased use of fossil fertilisers |



Novel applications of residual biomass result in RUC because they alter the current situation. RUC may have undesired consequences. Similar to LUC, these can occur either directly or indirectly. Direct consequences are the losses of the current functions, as shown in Table 4.2. This can result in disturbed supply chains, degraded agricultural soils, disturbance of ecosystems or loss of ecosystem services. Indirect consequences do not influence the biomass function directly but occur due to the replacement of a current function. For example, if residues used as animal fodder are devoted to new applications, the fodder has to be replaced with other sources, which may in turn lead to displacement effects such as iLUC [9,207]. If residues are used with the goal to avoid iLUC, as it is often argued, some applications may thus indirectly have the opposite effect.

Although RUC of residual biomass may have undesired consequences, it is worth considering. In some cases additional value may be achieved in combination with retaining the current function, while in others novel applications may achieve higher benefits than the current use. Especially low quality and waste streams may benefit from new processing. Biogenic waste that is currently incinerated may for example yield more energy through modern biogas installations. Other residues can be used first to produce energy or materials and subsequently extract nutrients for soil re-nourishment. In some cases, a compromise between current and new functions may be established, for example by applying mosaic landscape management allowing for different functions in different locations [206].

These examples show that residual biomass use for modern bioenergy or bio-based material production can be worthwhile. In some cases, it can achieve its promise as sustainable alternative to cultivated biomass, thereby avoiding land-use change and negative consequences related to it. However, the above-described challenges show that this strategy is not a silver bullet. It requires case-specific evaluation, determining the potentials and consequences of a changed resource use.

## 4.5 Biomass applications and sustainability issues

Next to the RUC impact, the overall contribution of biomass use to sustainability is also determined by the aspired application itself. This section discusses the relation between applications of residual biomass and sustainability.

Efficiency of resource use is an often-discussed aspect regarding biomass applications. Generally, more efficient use of resources is associated with greater sustainability [cf. 167]. There are different views on what efficiency entails. While some argue that all components and by-products of any given biomass resource should be used, including the re-use or recycling of waste streams, others refer to choosing the best application for each quantity of resource [167]. Different concepts address the optimisation of biomass applications, for example cascading principles, biorefinery concepts or prioritisation according to the value of the end product. They consider various applications, either prioritising between them, or aiming at producing multiple products. All three concepts generally favour the production of (higher value) bio-based materials. For energy production, mainly lower value or otherwise unusable residues or by-products are considered. Through re-use of by-products and waste streams, residual biomass has the potential to link up different sectors. One sector can use the residual streams of another, thus creating synergies. Residual biomass is then seen as another raw material flow, rather than a waste stream [208].

Even though increased efficiency of resource use may be advantageous, it does not necessarily lead to increased sustainability. The determination of efficiency is dependent on the objective of the application. Biomass is used to achieve a variety of different objectives, for example replacing fossil fuels, reducing GHG emissions, producing renewable energy, creating economic benefits or stimulating rural development [167]. However, not all goals are necessarily related to increased sustainability. Consequently, efficiency in reaching some of these objectives does not necessarily lead to increased sustainability. Different applications should be weighed against one another in order to define how residual biomass use can best achieve a contribution to sustainability. Sustainability is then not only a boundary condition for biomass use, but the actual main goal. Efficiency of biomass applications can then be measured in terms of reaching a more sustainable situation.

Potentials to contribute to sustainability not only lie with the reduction of GHG emissions, although that is one of the main drivers of the bioeconomy and an important sustainability goal. Another important sustainability challenge is the disturbance of global biogeochemical flows resulting, for example, from agricultural activities applying artificial fertilisers. Especially Phosphorus and Nitrogen distributions across the globe are dangerously disturbed, and biogeochemical flows have been identified as one of the planetary boundaries [209]. Recovery of minerals from biomass as an additional processing step offers the potential to reallocate minerals and replace artificial fertilisers, thereby counteracting this disturbance. Another chance lies with the production of environmentally friendly products. Although not all products that are bio-based are necessarily beneficial, new processes have the potential to create products that are for example less toxic or biodegradable, contributing to solving pollution problems.

## 4.6 Conditions for sustainable residual biomass use

The use of residual biomass as alternative for cultivated biomass offers several advantages, but it cannot be considered a silver bullet for a sustainable bioeconomy. Changing current use of resources, even if it means sourcing previously unused biomass residues, can have negative impacts outweighing the advantages. Whether residual biomass use contributes to sustainability depends on a variety of conditions, often influenced by regional differences. In this section conditions for sustainable use of residual biomass are discussed, considering existing sustainability criteria and building on the previous sections.

One approach to set boundary conditions for sustainable use of biomass resources has been the development of sustainability criteria or standards. Such criteria mainly demand that biomass applications achieve GHG savings in comparison to their fossil-based alternatives, and that biomass is not produced on land with high biodiversity or high carbon stocks [148,210]. Regarding residual biomass a distinction is made between agricultural, aquacultural, fisheries and forestry residues on the one hand, and all other waste and residues on the other hand. Criteria for the latter group are less strict, essentially reduced to GHG emission reductions [148]. Some argue to include a criterion ensuring that the extraction of residual biomass does not negatively influence soil quality [210]. Sustainability criteria are criticised for their restriction to certain bioenergy applications and the exclusion of impacts that are difficult to measure, such as iLUC [9,16]. Universal application to all resources and all applications as well as consideration of all effects would be beneficial to enable a level playing field.

The previous sections have shown that additional to the aspects addressed by current sustainability criteria it is crucial to consider the origin and current use or function of residual biomass. New applications always present a RUC. Both GHG emissions and influences on soil quality are valid concerns, but RUC can have additional environmental impacts such as biodiversity loss or iLUC, as well as influences on other supply chains currently using the residual biomass. To maximise the benefits, different potential applications, or combinations of applications, should be compared since they may contribute to sustainability in varying degrees. It has to be thoroughly investigated what the effects of RUC are, in comparison with the current use or function.

Table 4.3 presents a checklist that can be used by public or private actors considering the use of residual biomass to evaluate and compare the contribution to sustainability of different resource and application options. It is divided into three sections addressing the current use of residual biomass, the potential application and the impact of RUC. To determine the potential impacts of RUC, current uses and functions have to

Table 4.3 Checklist for sustainable residual biomass use.

| Topic | Relevance | Checkpoint |
|---|---|---|
| **Current Use** | Residual biomass may already be in use for another application or fulfil a function when left behind. Examples: Wood residues are used for the production of composite materials and landscape residues may fulfil ecosystem services when left behind, e.g. maintaining soil quality or offering habitats. | Is the biomass currently being used or does it fulfil any function?<br>Do the residues currently fulfil ecosystem services when left behind?<br>Can the current use be replaced sustainably? |
| **Potential Application** | Depending on sustainability goals, residual biomass can be used for a variety of applications. The measure of efficiency depends on these goals. If residual biomass is to contribute to sustainability, several aspects should be considered to weigh different application options. Furthermore, applications should be adapted to use residual biomass optimally. | Does the envisaged application contribute to sustainability efficiently? Consider the following aspects:<br>• Reduction of GHG emissions<br>• Replacement of fossil resources<br>• Mitigation of disturbance of biogeochemical flows (e.g. N, P recovery)<br>• Production of environmentally friendly products (e.g. non-toxic, biodegradable)<br>Are technologies, organisation and logistics adapted to use residual biomass optimally?<br>Are synergies between biomass processing sectors optimised? |
| **Impact of RUC** | Changing current use may cause negative impacts. Current supply chains may be disrupted, causing a switch to other resources and (i)LUC. Removing biomass from ecosystems can have negative impacts on the provision of ecosystem services. | Are ecosystem services reduced or lost as a consequence of RUC?<br>Are current supply chains interrupted?<br>Does the RUC cause (i)LUC?<br>Is the transition cost and energy efficient?<br>Do the benefits of new applications outweigh the negative impacts of RUC? |

be identified and valued. The consequences of loss or modification of these uses must be determined, considering possible sustainable alternatives. Next, different applications must be weighed, comparing their contributions to sustainability and determining the most beneficial application. They should be valued according to their potential to reduce GHG emissions, replace fossil resources, mitigate disturbance of biogeochemical flows and produce environmentally friendly products. Applications must be adapted to the specifics of residual biomass to maximise the resource efficiency. As discussed in Section 4.3, residual biomass can be difficult to access and of lower quality than cultivated biomass. Technologies and logistics should be adapted to minimise these disadvantages so that residual biomass can effectively replace fossil resources. Biomass processing in all relevant sectors should be adapted to enable optimal use of residual biomass and waste or by-products arising during processing. Striving for an efficient use of residues and waste streams furthermore has the potential to create synergies between different biomass applications and sectors. What is considered waste in one sector may well serve as input for other uses. Increased synergies provide great potential to increase sustainability in a bioeconomy and cope with competition for various applications. Efficient use of residual biomass links up well with sustainability concepts considering the reuse of waste as resources (e.g. circular economy, cradle to cradle). Finally, the impacts of the RUC have to be determined.

How benefits and costs of RUC are valued largely depends on the sustainability goals of the envisaged biomass application. The comparison should not be based solely on monetary terms. Current sustainability criteria only require a GHG emission reduction for certain residual biomass resources and are restricted to liquid bioenergy applications. However, RUC of all types of residues can have additional impacts that should be evaluated. The GHG emission impact and the potential to replace fossil resources are quantifiable, but impacts on soil fertility, iLUC and ecosystem services such as habitats and biodiversity are more difficult to value. Their consideration is, however, important to estimate all costs.

## 4.7 Conclusion

The transition to a bioeconomy can offer important steps towards a more sustainable situation, like the reduction of the unsustainable exploitation of fossil resources, reduction of GHG emissions and the provision of more environmentally friendly products. However, if land-use changes are required to produce biomass, negative impacts often outweigh the benefits. Production on marginal land and the use of residual biomass are often proposed as strategies for sustainable biomass supply. But the assumption that residual biomass use is always sustainable because it does not cause (i)LUC is inappropriate; it is not a silver bullet to ensure a sustainable bioeconomy.

When it comes to cultivated biomass, competition for land, (i)LUC and carbon payback times are some of the main concerns which should be addressed through sustainability criteria. Residual biomass is a different type of resource and requires different considerations. It is false to generalise that residues are waste streams that are currently unused, assuming their exploitation is always beneficial and applying less strict sustainability criteria. RUC to realise new applications always has consequences, whether the resource is currently used, left behind or enters waste treatment. Therefore, the sustainability of new applications has to be evaluated based on the effects of the RUC.

It is recommended that public and private parties considering the use of residual biomass include all potential impacts of RUC in the evaluation of new applications. These potential impacts furthermore show the complexity of interactions between different supply and demand systems for biomass. Choices between resources and applications should be weighed based on their contribution to sustainability in order to reach the objectives of a bioeconomy. Reliable methods to assess impacts that are difficult to quantify at the moment, such as iLUC or biodiversity, should be developed. Facing a great demand for biomass all resources that can be supplied sustainably are helpful. Residual biomass should not be considered waste but a potential resource, applying above-discussed conditions to ensure that it contributes to a sustainable bioeconomy.


Mowing of a slope, Lent, The Netherlands (S. Pfau)

# Chapter 5

## Residual biomass from Dutch riverine areas – from waste to ecosystem service

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## Abstract

Dutch riverine areas are managed intensively to ensure the provision of various ecosystem services. Vegetation management, including pruning and mowing, produces a woody and grassy biomass as a by-product. In the past, this residual biomass has been treated as a waste product. Now there is a change of perspective; biomass is valued as a potential additional ecosystem service instead of a waste product. In this study, we explore the transition from waste to ecosystem service of residual biomass in Dutch water management organisations. We found several trends in the organisation of biomass use. There is a development away from the traditional approach of choosing the cheapest or easiest way to get rid of biomass towards exploring various uses of biomass that fulfil additional, societally relevant, functions. This trend alters the organisation of vegetation management and subsequent biomass use. Selection based on sustainable biomass uses is gaining importance, and there is a growing desire within public organisations to be able to steer towards sustainable use of residual biomass. However, there is a lack of applicable, objective ranking instruments.

## 5.1 Introduction

In recent years, the use of biomass for various applications, such as energy and materials, has received increasing attention. The upcoming bio-economy is stimulated by various drivers, such as the need to reduce our dependence on fossil resources, the need to reduce greenhouse gas (GHG) emissions, environmental concerns and increasing demand for sustainable products, but also the expectation of a boost to rural development and other economic benefits [167]. Residual biomass is discussed as one of the important second-generation resources for bioenergy and bio-based products [34,35,211]. Using residues as input for new production chains transforms residual biomass from a waste into a resource. Residual biomass is increasingly considered an important resource because it potentially avoids several negative impacts associated with cultivated biomass [33]. Landscape management, for example, of roadside vegetation, municipal green and river floodplains, produces biomass as a by-product that can serve as input for the production of bioenergy and bio-based products. Large parts of The Netherlands feature riverine areas that require intensive landscape management. In the past, the residual biomass produced by vegetation management has been treated as a waste product, but now there is a change of perspective away from regarding it as waste towards valuing it as a potential additional ecosystem service. In the organisation of vegetation management, a shift has occurred from getting rid of biomass towards organising its sustainable use as a natural resource. In this paper, we explore the (possible) transition from waste to ecosystem service of residual biomass in Dutch water management organisations. We focus on the developments in current practice around using residual biomass from public lands and the accompanying organisational changes. Vegetation released during landscape management of public properties is a potentially important source of residual biomass. The research questions to be answered in this paper are:

- What are the current uses of residual biomass from riverine areas?
- What are the drivers for the different biomass uses?
- How is the use of biomass released during vegetation management organised and which organisational changes can be observed when biomass is considered an ecosystem service?

With this study we aim to inform landscape managing organisations, not only from the Netherlands but internationally, on possibilities to use residual biomass as an ecosystem service, providing information on biomass applications and required organisational changes. Other authors have investigated the potential of biomass from riverine landscapes as a provisioning ecosystem service [14] and compared the greenhouse gas emissions of different biomass uses quantitatively [16]. In this paper, we focus on the developments in current practices around the use of residual biomass and the accompanying organisational changes.

## 5.2 Background

### 5.2.1 Bioeconomy and residual biomass

Replacing fossil resources with biomass in the production of energy and materials is expected to improve the sustainability of products and production systems, but this contribution is not self-evident [167]. The production of biomass to fulfil rising demands for bio-based products requires productive land and is argued to cause both direct and indirect land use change [15,18,21]. Land use change can cause significant GHG emissions, and in many cases, it takes decades before initial emissions of carbon are offset by carbon savings of bio-based products [39,41].

One strategy that is often suggested to avoid the negative effects associated with land use change is the use of residual biomass [32,115,142,170]. Four types of residual biomass can be distinguished: agricultural residues, animal manure, organic waste and landscape residues [33,212]. Landscape residues may include biomass released during landscape management activities in various types of landscapes, such as forests, roadside vegetation, pastures and half-natural landscapes such as floodplains [33]. In the Netherlands, 14.5 Mton dry matter (DM) biomass was used for material and energy production in 2012, but the demand is projected to rise to 25 to 35 Mton DM by 2030 [213]. It is estimated that around 60% of the biomass currently used are imported from outside of the Netherlands. A Dutch study on the biomass potential for gas production estimates the amount of residual biomass released during landscape management in the Netherlands (including woody landscape biomass, natural grass and roadside vegetation) at about 2 Mton DM. A part of this biomass is currently used for renewable energy production in biomass installations and as co-digestion material in biogas production. Natural grass is sometimes applied as fodder, but most landscape residues are treated in composting installations [214].

### 5.2.2 Residual biomass as ecosystem service

In the case of necessary vegetation management in landscapes, such as roadside vegetation and floodplains, the provision of biomass is increasingly viewed as an ecosystem service. An interesting case for this change of perception is the vegetation management in riverine areas in the Netherlands. River systems are among the most important ecosystems in the world. The natural and semi-natural ecosystems of rivers provide ecological and socio-economic value, goods and services [215], which are now also described as ecosystem services. Numerous frameworks exist for defining and classifying ecosystem services, and there are different approaches to quantify and value them. It is a rapidly growing topic across various disciplines and organisations [216]. In short, ecosystems services are benefits people obtain from ecosystems. They include provisioning, regulating, cultural and supporting services [217,218]. Typical river ecosystem services are water safety, fresh water supply, flood mitigation, transport capacity, food and biomass. Ecosystem service concepts can offer a valuable approach to interpreting the links between humans and the natural environment and arguing for the conservation and restoration of natural ecosystems [219].

The Dutch river system provides ecosystem services that are of great social and economic value, including flood mitigation, navigation routes and the natural environment. Water management organisations focus on securing the provision of these ecosystem services. Large parts of the Netherlands are located in the delta of three major rivers (the Rhine, the Meuse and the Scheldt). This delta area is densely populated and especially vulnerable to peak discharges. Because the water conveyance capacity of the floodplains is lowered due to high and dense vegetation an important measure to manage flood risks is vegetation management. Since 2014, a new vegetation norm for the floodplains of the Meuse and the Rhine tributaries determines the permitted vegetation roughness per area, based on water safety considerations [220]. Vegetation has to be removed regularly to achieve the envisioned safety standard, requiring costly management measures. This has given rise to the idea of using biomass released during management measures, thereby (partly) re-paying the management costs and at the same time providing a valuable resource. The supply of residual biomass from publicly owned areas, based on yearly vegetation increments in the floodplains of the Dutch Rhine tributaries, is estimated at 370,953 tons DM of biomass, of which 87% are grassy biomass. This is equivalent to an estimated 353 Tera Joule of heat produced from woody biomass and 15 million $m^3$ of green gas from grassy biomass [16].

### 5.2.3 Sustainability ambitions and instruments

An increasing number of countries worldwide are pursuing explicit political strategies to expand and promote the bio-economy [221]. In the Netherlands, strategies are being developed to switch from fossil to green resources to tackle the challenge of resource dependencies and climate change. In the absence of large quantities of biomass resources, focus in the Netherlands lies on product development and the (chemical) processing industry to drive the transition, increasing the efficiency of biomass use and waste stream recycling [221,222]

The Netherlands has set ambitious goals for the bio-economy at the national level, but these do not specifically include the use of residual biomass from landscape management. However, a change in the perception of landscape residues can be observed. Increasingly, public organisations, including water management organisations, engage in projects that consider residual biomass as a useful, natural resource instead of a waste product. Traditional objectives of water management organisations, such as ensuring flood safety, realising appropriate natural environment management and creating a healthy living environment, are combined with the goal of using biomass as an ecosystem service. The provision of biomass then becomes a by-product of river management and water management organisations are stimulated to enter a new market.

One important operational barrier for reusing residual biomass is manifested in Dutch legislation. Under Dutch law, residual products, such as biomass from landscape management, are waste products. Their transportation, storage and use underlie strict environmental laws and regulations. To reuse residual biomass from landscape management for new products, it must undergo waste treatment (usually composting), after which its status is changed from a waste product to a resource.

For the execution of vegetation management, public organisations have several instruments that can help to steer towards sustainability. In general, three options to organise vegetation management can be considered: Water management organisations can execute the management themselves, they can enter a tendering procedure and choose a market party for the execution based on the best price only, or they can include additional criteria, other than price, in the tendering procedure. To steer towards sustainability in a tendering procedure, public organisations can either formulate requirements up front or leave the specific approach towards increased sustainability up to the market parties, including evaluation criteria for sustainability in the selection procedure. The Dutch ground-, road- and water engineering sector developed two instruments to evaluate sustainability in tenders: the “$CO_2$ performance ladder”, to stimulate $CO_2$ awareness and “DuboCalc”, based on Life-cycle assessment (LCA). Both instruments enable a sustainability rating of the engineering and execution of works, the use of materials, energy and the disposal of waste (http://www.duurzaamgww.nl). However, sustainable use of residual resources released during vegetation management is not included. In the upcoming bio-economy, this is a new phenomenon, and it appears that no formal evaluation instruments have yet been developed. This corresponds to the lack of specific goals for the use of residual biomass from landscape management in the different National and regional policy documents from water management organisations.

## 5.3 Methods

We researched the use of biomass in current water management practices in three types of organisations involved in water management: Rijkswaterstaat, the executive part of the Dutch Ministry of Infrastructure and Water Management, the Dutch State Forestry Service and Dutch water boards. In this study, we are only considering biomass released from public lands, owned by one of these organisations.

Rijkswaterstaat is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands. This includes the main roads, the main waterway network and water systems. Rijkswaterstaat owns and manages 2,137 km of canals and rivers and the strip of land along the river beds. The main goal for the execution of vegetation management by Rijkswaterstaat is to reduce the vegetation roughness to secure the water discharge capacity and reduce flood risk.

The Dutch State Forestry Service is a public enterprise commissioned by the Dutch government to strengthen the position of the natural environment in the Netherlands. They are manager and owner of 265,000 ha of forest and national parks across the Netherlands. Their main goal is to conserve, develop and sustain the natural environment, but also to contribute to the realisation of national priorities, which include wood and biomass production and water safety strategies along the coast and large river systems [223]. The State Forestry Service is responsible for the vegetation management on their grounds in the floodplains.

The Dutch water boards are regional governmental bodies charged with managing regional water systems including water levels, water barriers, water quality and sewage treatment. There are 21 water boards in the Netherlands, and together they manage a total 235,000 km of ditches and small rivers (https://dutchwaterauthorities.com/about-us/). They are responsible for the vegetation management in these water systems, aiming at regulating water levels and water quality.

We contacted various people engaged in vegetation management at Rijkswaterstaat, the State Forestry Service and at all water boards in the Netherlands. We created a database of vegetation management practices in these organisations, containing details about the organisation of vegetation management and biomass use. We gathered information from 19 of the 21 water boards, the three relevant units of Rijkswaterstaat and five relevant regional units of the State Forestry Service, which feature riverine areas in their management areas. We then analysed the organisational arrangements of vegetation management in these organisations, which are described in Section 5.4.2. To enable a closer look at both the organisation and the drivers behind biomass use, we studied exemplary cases from each organisational arrangement and, where possible, each (type of) river management organisation. For a total of 13 cases, we conducted semi-structured interviews with employees responsible for vegetation management within their organisation. As is appropriate for open-ended, explorative questions, we purposefully selected interviewees that would help to understand the problem and research questions at hand [55]. The interviewees represent the medium or lower management within their organisations. We chose them because we valued their familiarity with current vegetation management practices. Semi-structured interviews were chosen to ensure that the same topics were addressed in each interview. At the same time, this approach leaves room for individual conversations, where opinions and experiences of interviewees can be addressed. The interview topics were based on observations from the above-described database of vegetation management practices, and biomass uses developed for this study. We developed an interview guide with primary and follow-up questions to structure the interviews and ensure that all topics were addressed. During the interviews we discussed four main topics:

1. Current execution of vegetation management.
2. Organisation of and responsibility for vegetation management.
3. Current use of biomass released during vegetation management and related drivers and decision-making processes.
4. Visions and ambitions concerning biomass use of the water management organisation.

All interviewees were informed about the interview topics in advance to allow them to prepare themselves. The interviews were recorded and transcribed. The transcripts were then analysed in line with a thematic analysis approach. We used the qualitative data analysis (QDA) software package ATLAS.ti (version 7) to identify common themes in the interviews, coding the transcripts in several steps. During analysis, the interviewees were regarded as stakeholders with detailed knowledge of and personal experience with vegetation management and biomass use in current practice. Their opinions are not necessarily representative for the vision of their entire organisation, but they were regarded as knowledgeable on their organisation’s strategy.

To broaden our insights and hear more about higher management perspectives, we also conducted three interviews with managers of working groups or departments concerned with biomass use positioned close to the top management of the three organisations. In these interviews, we focused on organisational visions and ambitions and goals for biomass use in the future. An overview of the interviews is shown in Table 5.1.

Table 5.1 Overview of interviews. One interview was conducted per organisation part; if that interview delivered sufficient information about multiple organisational arrangements, it is listed under each arrangement.

| Organisational arrangement | Organisation | Organisation part |
|---|---|---|
| **Tenancy** | Water board | Rijn en IJssel |
| | Rijkswaterstaat | Tenancy contracts |
| | State Forestry Service | Maasheggen |
| | State Forestry Service | Gelderse Poort |
| **Passed to adjoining landowner** | Water board | Brabantse Delta |
| | Water board | Scheldestromen |
| | Water board | Aa en Maas |
| **Passed to contractor** | Water board | Limburg |
| | Water board | Vallei en Veluwe |
| | Rijkswaterstaat | Standard maintenance contracts |
| | State Forestry Service | Maasheggen |
| **Ranked tendering** | Water board | Schieland en de Krimpenerwaard |
| | Water board | Aa en Maas |
| | Rijkswaterstaat | New contract region IJssel |
| **Pre-determined use** | Water board | Brabantse Delta |
| | Water board | De Stichtse Rijnlanden |
| **In-house** | Water board | Brabantse Delta |
| | Water board | Vallei en Veluwe |
| **Additional interviews centralised groups** | State Forestry Service | Manager product group biomass |
| | Rijkswaterstaat | Manager business unit natural capital |
| | Water board | Chairman working group biomass of the "energy- and resources factory" initiative of the Dutch water boards |

## 5.4 Results

In this section, we present the results of our analysis of both the database and the interviews. First, we will describe the current uses of residual biomass from riverine areas and briefly discuss the drivers for the different uses. Subsequently, we describe the different organisational arrangements we identified and discuss the relationship between the biomass uses and corresponding organisational arrangement. Finally, we will present some notable emerging issues that arose while discussing trends and expectations of future values and markets for residual biomass from landscape management in the interviews with both practitioners and managers.

### 5.4.1 Current biomass uses

From the 13 semi-structured interviews with practitioners responsible for vegetation management, we identified 12 different biomass uses (Table 5.2). We distinguish between woody (tree trunks, branch wood, wood clippings) and grassy biomass (grass/herbs from dykes, ditches and floodplains).



Table 5.2 Residual biomass uses in current water management practice.

| | **Biomass use** | **Description** |
|---|---|---|
| **Woody** | Woodchips | Processing of branch wood into woodchips for biomass boilers |
| | Construction wood | Harvested trees of sufficient quality processed by the wood industry |
| **Grassy** | Biogas | Co-fermentation of grassy biomass |
| | Grass pellets | Compression of grassy biomass into pellets used in biomass boilers |
| | Leave at site | Biomass left at the maintenance site or spread out in direct vicinity |
| | Local soil application | Local use of grassy biomass on agricultural land, where it is mixed with soil aiming at an improved soil organic matter (SOM) content |
| | Compost | Industrial composting of biomass, producing compost for applications in agriculture and as peat replacement in soil production |
| | Grass fibre | Processing of grassy biomass into fibres for fibre board or paper and carton production |
| | Grazing | Grazing of grassy biomass |
| | Hay | Processing of grassy biomass into hay for animal feed |
| | Feed organic agriculture | Processing of grassy biomass into animal feed for organic agriculture |

Both woody and grassy biomass were used to produce energy as either woodchips, biogas or grass pellets. Most interviewees conveyed the opinion that energy is considered a low-value application. Some stated that when biomass is used for energy, it must at least have a positive impact on the $CO_2$-balance of the organisation, which is not always clear or known. Only one interviewee had a positive feeling about energy uses, stating he believed it is better to use the energy from residual biomass than from non-renewable sources, based on $CO_2$ emissions.

Although harvesting of trees seldom occurs in the vegetation management of water management organisations, trees of sufficient quality are sometimes used in the construction wood industry. The market for construction wood is well developed and selling wood to the wood industry is a common practice that also generates some revenues. Grassy biomass is sometimes also used as a source for construction material. The grass fibres are used for fibre boards and paper- or cardboard production. These techniques are emergent and sometimes still have a pilot status. Water management organisations consciously chose to participate in such pilots, because they want to explore the possibilities of residual biomass and identify valuable uses.

Water boards, especially, often leave grassy biomass from ditch banks and channels at the maintenance site or in the direct vicinity (at the top of the slope). The main driver is to avoid transport costs and also possible damage to land, roads and dykes as a result of transport. In some cases, it is practically impossible to remove the biomass, because there is a lack of space for machinery. In other cases, the biomass is passed to the adjoining landowner, who has to remove it and usually spreads it out over adjoining land. Passing biomass to the adjoining landowner is also seen as traditional within Dutch water boards. 'Leave at site' is often seen as a 'default' option, because it is the cheapest solution with the least handling. It is, however, not always desirable, since leaving the biomass at site causes mineral deposition, which is not always in line with environmental goals and can provide a substrate for weeds like thistles and nettles, which is undesirable for adjoining farmers. In many situations, especially in flood-prone areas along the major rivers, biomass may not be left behind due to safety considerations, as it may reduce water discharge capacities.

Whenever biomass cannot be left behind, composting is the default option. It is described as one of the more traditional biomass uses, and almost all of the interviewees see composting as one of the least desirable applications. In the Netherlands, composting is a waste treatment, which means that a gate-fee has to be paid when depositing the material at the composter. On top of the gate-fee, there are also transport costs, which make composting an expensive biomass use.

Local soil application of biomass is receiving growing interest and is regarded as an alternative for composting by some interviewees. The grassy biomass is mixed with agricultural soil aiming at improving the soil organic matter (SOM) content. Before ploughing it into the ground, the biomass can undergo different pre-treatments with the objective to make the organic content more easily available for the soil. One reason to choose local soil application is the relationship with farmers. Farmers are looking for ways to improve the organic matter content of their land and, therefore, approach water management organisations for their residual biomass. Local soil application is also perceived as a high-value biomass use by most interviewees because the application is local and assumed to improve agricultural production. It is also expected to improve the water retention capacity of the soil, which can contribute to the water management goals of the organisations. Finally, local soil application is cheap, because transport and deposition costs for composting are avoided.



Grassy residual biomass is used to feed livestock, either in the form of hay or by grazing. The use of residual biomass for feed is considered valuable, especially when it would otherwise be treated as waste. It can also generate some revenues. However, it is not always possible to produce hay due to weather conditions. When the quality is insufficient, the biomass is brought to the composter. A special category for feed is hay and grazing for organic agriculture. Organic farming is described as more valuable than traditional farming by some interviewees. Floodplains are particularly interesting for organic farmers because fertilisers and pesticides are prohibited on these sites.

In many cases, interviewees referred to the relative value of applications as a driver for the choice of biomass uses. Sometimes this was described rather vaguely as a feeling that certain uses are societally more or less useful, in other cases, concepts for prioritising different applications were cited: Either the so-called 'Lansink ladder' or the biomass value pyramid, both well-known concepts in the Dutch bio-economy debate were referred to. The Lansink ladder is a standard in waste management, ranking options such as recycling, energy recovery and disposal from favourable to unfavourable. The value pyramid is a similar concept, but specific to the bio-economy. It ranks different biomass applications and sectors, for example, food, chemicals and fuels in terms of added value. Both of these concepts are interpreted by interviewees to prioritise applications for food production or material reuse of biomass over energy applications and composting.

### 5.4.2 Organisational arrangements

From our database of vegetation management practices, we identified six different organisational arrangements based on the type of contract underlying vegetation management and on who is deciding about the biomass use (Table 5.3).

Table 5.3 Organisational Arrangements.

| Organisational arrangement | Contracting for vegetation management | Decision about biomass use |
|---|---|---|
| **Tenancy** | Tenancy | Tenant |
| **Passed to adjoining landowner** | In-house or tendering | Adjoining landowner |
| **Passed to contractor** | Tendering | Contractor |
| **Ranked tendering** | Tendering | In-house ranking procedure during tendering |
| **Pre-determined use** | Tendering or Tenancy | In-house |
| **In-house** | In-house | In-house |

**Tenancy:** Use of land, including obligations for vegetation management, are offered via a tendering procedure. Tenants have to submit a bid for a certain piece of land. Tenders include guidelines and requirements for the tenant, but the tenant decides how biomass is used.

**Passed to adjoining land owner:** Most Dutch water boards traditionally apply a so-called 'reception obligation', which means that landowners adjoining to the managed site are obliged to receive and handle the residual biomass. This way, water boards do not have to handle transport or disposal of biomass. The adjoining landowner determines the biomass use.

**Passed to contractor:** Vegetation management is executed by a contractor who is selected via tendering. The ownership of the biomass is passed to the contractor, and the contractor decides how the biomass is used. No requirements regarding the biomass use are specified, other than that it has to be removed and treated according to the law.

**Ranked tendering:** Similar to the arrangement 'passed to contractor', the vegetation management is executed by a contractor who is selected via tendering. In the description of the tender requirements regarding biomass use are specified. During the selection procedure, the tenderer can score points or a fictitious discount on the price he offers for the service, based on the biomass use he proposes. Requirements are, for example, 'for every 10% of the biomass which is used more sustainably the tenderer is rewarded with a fictitious discount' or 'come up with a plan for improvement and investment proposals regarding vegetation management'. The tenderer with the best overall score on (discounted) price or points wins the procedure.



**Pre-determined use:** The vegetation management is executed by a contractor selected via tendering. The use of the biomass is pre-determined, which means that the water management organisation prescribes the use of the biomass in the contract, based on previous arrangements with a biomass user.

**In-house:** Both the execution and the decision making on the biomass use is done by the water management organisation.

### 5.4.3 Relation between biomass uses and organisational arrangements

To see whether certain organisational arrangements trigger specific biomass uses (or the other way around) we looked at the different biomass uses per organisational arrangement. For each interview, we recorded what kind of biomass use occurred and to which organisational arrangement(s) it was linked. Table 5.4 presents the biomass use per organisational arrangement as a percentage of the total number of uses mentioned for each organisational arrangement. The organisational arrangement of tenancy mainly co-occurs with the biomass uses hay and grazing, while 'passed to adjoining landowner' is only linked to the biomass uses 'leave at site' and 'local soil application'. The largest variety in biomass uses is seen with the organisational arrangements 'passed to contractor' and 'ranked tendering'. 'Pre-determined use', on the other hand, is not linked to many different biomass uses.

Table 5.4 Relation organisational arrangement and biomass use. Biomass use per organisational arrangement is presented as a percentage of the total number of uses mentioned for each organisational arrangement.

| | | **Organisational arrangement** | | | | | |
|---|---|---|---|---|---|---|---|
| **Biomass type** | **Use** | **Tenancy** | **Passed to adjoining landowner** | **Passed to contractor** | **Ranked tendering** | **Pre-determined use** | **In-house** |
| **Woody** | Woodchips | 0 | 0 | 18 | 0 | 0 | 11 |
| | Construction wood | 0 | 0 | 5 | 0 | 0 | 0 |
| **Grassy** | Leave at site | 9 | 60 | 14 | 0 | 0 | 33 |
| | Compost | 9 | 0 | 32 | 27 | 33 | 22 |
| | Grazing | 36 | 0 | 0 | 9 | 0 | 0 |
| | Hay | 36 | 0 | 9 | 9 | 33 | 11 |
| | Local soil application | 9 | 40 | 14 | 0 | 33 | 22 |
| | Biogas | 0 | 0 | 5 | 18 | 0 | 0 |
| | Grass pellets | 0 | 0 | 0 | 9 | 0 | 0 |
| | Grass fibre | 0 | 0 | 5 | 18 | 0 | 0 |
| | Feed organic agriculture | 0 | 0 | 0 | 9 | 0 | 0 |
| **Total** | | 100% | 100% | 100% | 100% | 100% | 100% |

### 5.4.4 Biomass uses: trends, values and market

Discussing trends and expectations of future values and markets for residual biomass from landscape management with the interviewees revealed some interesting issues. Some interviewees had never thought about the potential and possibilities of residual biomass and preferably would leave the responsibility to the contractor. Others noticed that residual biomass from landscape management is ‘hot’ and that they are urged by their higher management to ‘do something’ with biomass. Almost all interviewees pointed out that financial aspects are not the only thing to consider when valuing the use of biomass, but that social, ecological and environmental values are also highly important. A dilemma was felt between creating income and creating societal or environmental values and some questioned if it was possible at all to responsibly harvest biomass from ecologically valuable areas. Most of the interviewees saw societally responsible use of biomass as a prerequisite and stated that higher costs are justifiable if the biomass use contributes to other goals or create other values.

Composting was often described as the least valuable biomass use, and most organisations are looking for 'more sustainable uses than composting' although 'more sustainable' was not specified further. In general, local use is considered of high value and export of biomass away from the vicinity of the management site, for example, for materials or energy, is perceived as less desirable. However, if a contractor can profit from selling biomass, most organisations expect that this will be reflected in the price they pay for the execution of the vegetation management, stimulated by competition between bidding contractors. Organisations sometimes also choose not to interfere when contractors find new ways to market biomass because they prefer new biomass uses over composting. Some contractors are now trying to develop new revenue models for the use of residual biomass from landscape management.



Many interviewees argued that it is unclear what the possibilities and values of residual biomass are and, therefore, they participate in pilots for the development of new techniques. They investigate, for example, whether alternative mowing regimes can improve the quality of the biomass (less sand, dryer) to make it more suitable for specific new biomass applications. Some organisations are willing to invest in these pilots, even though the cost may be higher than the initial financial benefits. The choice to participate in a pilot is not based on calculations or $CO_2$-balance, but on a general feeling of a useful direction.

Expecting the value of biomass to increase, Rijkswaterstaat recently changed the ownership over residual biomass in all forthcoming tendering procedures. Formerly, the ownership passed from Rijkswaterstaat to the contractors, but now it remains with Rijkswaterstaat. This way they can decide what to do with the biomass without interference by the contractor. One of the water boards has prescribed that all biomass must go to a central point so that it can keep track of the amount of biomass released. This can help them to participate in new business cases. Most water management organisations do not have official ambitions or goals regarding biomass use, but some have sustainability goals, which in some cases may also apply to biomass use.

## 5.6 Discussion

In this paper, we described how water management organisations organise the use of residual biomass, a by-product of their vegetation management activities, and what their expectations are regarding its use in the future. Residual biomass, formerly seen as a waste product, is now increasingly viewed as a potential resource. We found several trends in the organisation of biomass use. In Section 5.4.1, we described the various uses of biomass that are currently realised. We found that there is a development away from the traditional approach of choosing the cheapest or easiest way to get rid of biomass towards exploring various uses of biomass that fulfil additional, societally relevant, functions. This trend alters the organisation of vegetation management and subsequent biomass use: selection of sustainable biomass uses is gaining importance in the choice of organisational arrangements. Both the water management organisations themselves and the contractors and market parties involved can play a role in this. In Section 5.4.3 we showed that the more traditional organisational arrangements of 'tenancy' and 'passed to adjoining landowner' result mostly in the more traditional biomass uses that one would expect. The organisational arrangements that transfer the responsibility for biomass use to contracted market parties deliver a greater variety of biomass uses, including some newer applications relevant for the upcoming bio-economy, such as bioenergy (e.g., biogas, woodchips) and bio-based products (e.g., grass fibres). Greater control of the water management organisations over biomass use, as in organisational arrangement 'pre-determined use' and 'in-house', does not result in the same variety, but we did encounter that some organisations use these arrangements to participate in pilots, experimenting with newer biomass uses that are not ready for the market yet (see Section 5.4.4). It appears that a new market is developing around the use of residual biomass from landscape management, and both contractors and water management organisations are reacting to this, for example, by changing ownership arrangements in tendering (see Section 5.4.4). While in some cases traditional organisational arrangements and biomass uses prevail, in others a phase of trial and error seems to develop, exploring the potential of this new market. It would be interesting to research this further by comparing the development with other newly developing markets, for example, of other natural resources or other ecosystem services.

Methods of public organisations to steer contracted works towards more sustainability until now focused on the execution of works and the use of materials (see Section 5.4.2). In this study, we found that recently new instruments are being developed and applied, in which the sustainable use of residual biomass is being promoted specifically. In all three types of water management organisations, we saw examples of the organisational arrangement ‘ranked tendering’, where the use of biomass is one of the ranking criteria. The methods to rank different uses in the tendering procedure, however, differed substantially. In all interviews addressing this organisational arrangement, it was expressed that formal, objective comparison of biomass uses was difficult due to a lack of ranking methods. Ranking was instead based on innovations, estimated position in the biomass value pyramid or a general feeling of societal relevance. In contrast to the execution of work and use of materials, the ranking of sustainability of resource and by-product uses is not yet institutionalised and there is no evaluation system in place, resulting in a trial and error approach and uncertainty.

There is currently a lack of consensus in the scientific community about the sustainability of the bio-economy in general, and even more so on the best way to use biomass. On the one hand, it is argued that bioenergy is important to reach renewable energy goals and mitigate climate change [150]. On the other hand, bioenergy is criticised as being inefficient in actually reducing carbon emissions and competing with other land uses; biomass should, therefore, only be applied for biomass material uses [28]. This lack of scientific consensus may explain why applicable, objective ranking instruments in public tendering are missing, and no objective ranking instruments were applied in the public tendering procedures observed in this study. Ranking criteria are, however, gaining importance, since there is a growing desire within public organisations to be able to steer towards sustainable use of residual biomass.

The lack of ranking criteria leaves room for interpretation, revealing a dilemma between evaluating based on function or costs. Different biomass uses have differing functions and societal relevance. In various interviews, it was mentioned that bioenergy is seen as a low-value application of biomass. Bioenergy was consequently often excluded or kept to a minimum in the choice of biomass uses. However, in practice, this was only true for bioenergy production from grassy biomass. In the case of woody biomass, the use as woodchips for energy production was the most chosen biomass use, because, in contrast to grassy biomass, there is a market for woodchips for energy and this biomass use is therefore economically attractive. A similar pattern emerged for biomass uses for soil improvement: many interviewees elaborated on the importance of improving soil quality in agricultural areas, both to ensure yields in the future and to achieve a greater water retention capacity in the soil surrounding water systems. But while compost is a classic and proven product to improve soil quality, composting is seen as a very low-value biomass use, mainly because it is depicted as simply a waste treatment method. Local soil application, aiming at using biomass as a SOM improvement on fields directly, is preferred by almost all interviewees. However, the potential of this direct application in actually increasing SOM is not proven. While composting and local soil application are assumed to fulfil the same function, composting is argued to be of lower value. Composting is currently the most expensive biomass use for water management organisations, while with local soil application the biomass can now be deposited for free or even generate some income.

In both examples of bioenergy application and soil improvement, the value of a biomass use is in the practical evaluation mixed with costs, and the costs are in the end the most influential factor, even though the main argumentation is based on the value of the biomass use. This makes the evaluation of sustainable biomass uses rather unclear and subject to change with developing markets and technologies. The consideration of bioenergy as a low-value product may also be related to cultural values. Prioritisation concepts such as the biomass value pyramid are particularly popular in the Netherlands, while internationally other values might prevail, for example, prioritising bioenergy for its potential to achieve $CO_2$ benefits by replacing conventional energy sources. Since there is no scientific consensus on the most sustainable use of biomass, it is not possible to give advice on the one best biomass use at this point; further research is required to develop ranking criteria for the choice of biomass uses. It is recommended to promote this research to enable a choice of sustainable applications and avoid the confusion of societal value and cost. If biomass applications that are now not preferred options due to higher costs turn out to be of greater societal value, efforts could be undertaken to make these uses more attractive.

The changing organisation of biomass use observed in this study does not necessarily result in economic advantages for water management organisations. There are various drivers for the engagement in residual biomass use, as described in Section 5.4.1. Saving or earning money is, therefore, not necessarily the most important reason for public organisations to think differently about residual biomass. There is also growing attention for the societal relevance of sustainable use of resources and the wish to contribute to societal goals. A preference for 'valuable' use of biomass was expressed by many of the interviewees, but interpretations of value varied and were often subjective, similar to the ranking criteria in 'ranked tendering'. Lack of ranking criteria may influence the choice of biomass uses, but it is unclear whether it also influences the choice of organisational arrangement. In some cases, it was mentioned that the choice of biomass use was left to contractors, trusting that market mechanisms would result in societally relevant use.



Even though financial considerations appeared to be not the only or most important driver to think differently about residual biomass use, we did find that some organisations expect the value of biomass to increase in the future. In the developing bio-economy, they expect that demand for biomass will rise and possibilities to use lower-value residues will be developed further. This also results in alterations of the organisation of vegetation management: as described in Section 5.4.4, Rijkswaterstaat now remains the owner of residual biomass instead of passing it on to the contractor. This expectation of a higher value of biomass may, however, be misleading in the long term. If the demand for biomass, and, therefore, its value, increases in the future, provision of biomass will become more lucrative. Biomass from riverine landscapes will then have to compete with biomass from specific production grounds. Water management organisations will probably not be able to compete on price, because biomass harvesting is much less efficient in floodplains and along ditches than on fields or in production forests. In their consideration of vegetation management, water management organisations should, therefore, keep in mind that residual biomass provision is only a by-product, while the main product is a well-managed landscape, fulfilling the main water-related goals of the organisations. Exploiting biomass as an additional ecosystem service may contribute to reducing management costs, but it is unlikely that significant revenues will be generated in the future. Water management organisations, therefore, should not focus on biomass production and expect to achieve more than a reduction of costs. Rather, they should strive for sustainable and societally responsible use of biomass as a by-product, in accordance with their role as public organisations.

## 5.6 Conclusion

Residual biomass from landscape management is increasingly viewed as a promising, sustainable resource for the international bio-economy. The Netherlands is a useful case study to analyse the use of residual biomass that was formerly considered a waste product. In this study, we showed that useful applications of residual biomass are already current practice. The consideration of biomass as an ecosystem service instead of a waste product is a useful frame to realise societal value. A new market appears to develop around residual biomass use, and this study showed that water management organisations are reacting to this by developing new tendering procedures, changing biomass ownership and engaging in pilot projects to explore new applications. Financial considerations, however, appear not to be the only driver to reconsider the use of residual biomass. Using biomass for societally relevant or 'valuable' applications is another important driver, influencing the choice of biomass applications.

Residual biomass from landscape management is currently used for multiple applications, including both energy and material applications. No formal, objective evaluation methods are applied or available. More scientific research is needed supporting the development of objective methods to compare the sustainability merits of different biomass applications. Currently, the lack of ranking criteria results in a trial and error approach and uncertainty. Using prioritisation concepts such as the biomass value pyramid as orientation for evaluating uses results in a preference for material uses over bioenergy. Furthermore, in practice, considerations of societal value of biomass use are mixed with costs. Water management organisations should strive for sustainable and societally responsible use of biomass as a by-product of landscape management. Ranking criteria to prioritise between different biomass uses, based on both general contributions to sustainability, but also local needs and opportunities for biomass uses, such as depleted soils or demand for renewable energy provision, should be developed to help with these efforts.

Landscape management practices should be adapted to make optimal use of residual biomass as an ecosystem service. Public organisations can play an important role in the development of residual biomass use in the Netherlands and internationally. They are generally in charge of landscape management and have a responsibility to use ecosystem services sustainably. Changing tendering procedures to include sustainability evaluation of biomass harvest and biomass use can stimulate creative solutions to collect biomass, instead of leaving it behind, and finding feasible, societally relevant applications. Vegetation management practice can furthermore be optimised to enable efficient residual biomass harvesting for sustainable applications, for example, combining mowing and pruning activities with direct biomass collection. Residual biomass use can also be promoted by pilots and innovation, to find new efficient applications for residual biomass. However, water management organisations should keep in mind that residual biomass is only a by-product of a well-managed landscape and biomass harvest should not be the main goal of vegetation management.

**Floodplain vegetation Breemwaard, The Netherlands (W. van Iersel)**

# Chapter 6

## Life cycle greenhouse gas benefits and burdens of residual biomass from landscape management

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## Abstract

The use of residual biomass for the production of bioenergy and biomaterials is often suggested as a strategy to avoid negative effects associated with dedicated biomass production. One potential source is biomass from landscape management. The goal of this study was to find the lowest net greenhouse gas (GHG) emissions of various applications of residual biomass from landscape management. GHG balances of thirteen residual biomass applications were calculated and compared to their respective conventional counterfactuals. As a case study, the potential contribution to climate change mitigation through the use of residual biomass available from vegetation management in floodplains of the Dutch Rhine delta were quantified. The greatest GHG benefits are achieved when using woody biomass to produce heat (-132 kg $CO_2$-eq./ tonne wet biomass) and grassy biomass to produce growth media (-229 kg $CO_2$-eq./tonne wet biomass). In contrast, composting grassy biomass for fertiliser replacement on agricultural fields results in the largest GHG burdens of 62 kg $CO_2$-eq. / tonne wet biomass. The findings imply that residual biomass from landscape management can contribute to both GHG benefits and burdens, depending on the application. Higher benefits were found for bioenergy than for biomaterial applications. Biomass applications should be chosen with care and consideration of their counterfactuals.

## 6.1 Introduction

Bioenergy and biomaterials may contribute to a reduction in fossil fuel use and the mitigation of climate change [17]. The dedicated production of biomass requires significant amounts of land and water, which can lead to an increase in water scarcity and both direct and indirect effects of land-use change. In many cases, greenhouse gas (GHG) emissions caused by land-use change outweigh the GHG savings of bioenergy production for years to decades [20] or even longer [14]. The use of residual biomass, rather than dedicated biomass production, can avoid negative effects associated with land-use change and water use Creutzig et al., [17] and is recommend to policymakers Dornburg et al. [224]. Residual biomass includes harvesting and processing residues from agriculture and forestry, animal manure, biogenic waste streams from industry and consumers, and residues of landscape management [31]. Landscape residues include biomass released during vegetation management in various types of landscapes, for example roadside vegetation, pastures and semi-natural landscapes such as floodplains [33].



Various publications have addressed the GHG emissions of bioenergy produced from residual biomass reporting potential GHG savings in comparison to reference systems, for example woody biomass residues from Italian orchards [225], forest residues in the UK [226] and cattle manure [227]. Several studies compare the climate impacts of biomass usage for different forms of bioenergy or biomaterials. For example, Gerssen-Gondelach et al. [228] analysed a variety of feedstocks, pre-treatment technologies and applications. The authors calculated avoided GHG emissions and found beneficial results for almost all routes analysed. Kim and Song [229] compared the recycling of wood waste into either energy or materials and reported GHG savings for both. Recchia et al. [230] analysed the environmental benefits of energy derived from riparian vegetation in Italy and Boscaro et al. [231] calculated GHG impacts of using grass obtained from landscape management of riverbanks for biogas production in Italy. Both studies report significant GHG benefits and are discussed further in Section 6.4. No previous studies have investigated the optimal use of residual biomass from riparian vegetation, or from landscape management in general, comparing various bioenergy and biomaterial applications from a GHG emission perspective.

This study quantified the potential contribution of residual biomass available from vegetation management in floodplains of the Dutch Rhine delta to climate change mitigation through bioenergy and biomaterial production. The Dutch Rhine delta is densely populated and has a relatively high flood risk due to expected increases in peak river discharges as a result of climate change [232]. This has led to extensive and ongoing flood risk management [233], including frequent riparian vegetation management to increase the water conveying capacity of floodplains [234]. Vegetation management based on cyclic rejuvenation can be applied to achieve optimal biomass removal [235], while at the same time yielding a continuous biomass supply [222]. Vegetation management is costly, giving rise to the idea of residual biomass usage to (partly) repay management costs, while providing a valuable resource for sustainable products.

The goal of this study was to find the lowest net GHG emissions from various applications of residual biomass derived from landscape management (such as energy, material and feed uses). The GHG benefits or burdens of such applications are calculated in comparison with the emissions of their respective conventional energy and material counterparts, which are referred to as *counterfactuals* (cfl.). The consideration of counterfactual emissions, as proposed in this study, enables the comparison of net GHG emissions across different types of applications (e.g. energy *vs.* material applications), and can be applied to any source of residual biomass. This study demonstrates how landscape management residues can contribute to climate change mitigation, focusing on thirteen applications of residual biomass from Dutch floodplain management.

## 6.2 Methods

### 6.2.1 Biomass applications and counterfactuals

Residual biomass harvested during vegetation management was categorised into: (1) woody biomass from forests and shrubs, and (2) grassy biomass from reeds, herbaceous vegetation and natural grassland (adapted from Koopman et al., 2018). Information on current applications for both types of biomass was collected through semi-structured interviews with water management organisations involved in the management of vegetation in publicly owned areas of Dutch floodplains. These include the executive part of the Dutch Ministry of Infrastructure and Water Management, the state forestry service, and several water boards. Some of these interviews were conducted during a parallel study (Chapter 5).

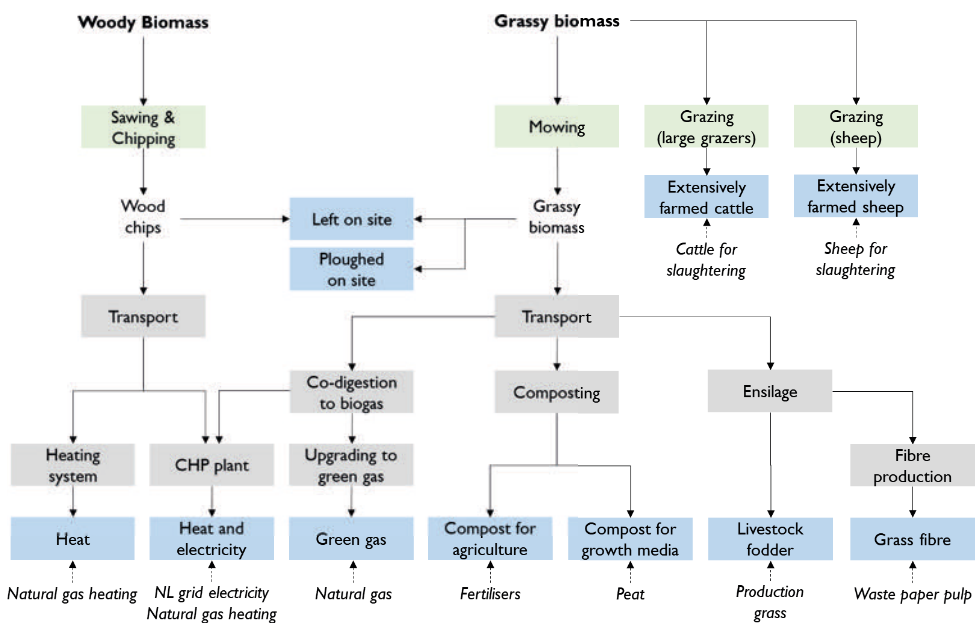


Figure 6.1 Schematic presentation of biomass applications and counterfactuals analysed in this study. Vegetation management activities are shown in green, transport and processing steps in grey and applications in blue. Counterfactuals are indicated in italic. Both woody and grassy biomass may be left on site or applied in combined heat and power (CHP) installations (grassy biomass after conversion to biogas), resulting in 13 applications.

This inventory revealed a total of thirteen biomass applications that are realised in current practice and can be subdivided into four categories: (1) left or ploughed on site, (2) grazing, (3) energy production and (4) material production. Figure 6.1 shows the applications, transport and processing steps and counterfactuals. Table 6.1 provides short descriptions of the applications. An extensive description and rationale for the choice of counterfactuals is included in the Appendix (A1).

Table 6.1 Description of biomass applications and counterfactuals. Includes the acronyms used in the text, the name of each application, a short description and the counterfactuals. An extensive description and rationale for choice of counterfactuals is included in Appendix A1.

| Acronym | Application | Description | Counterfactual |
|---|---|---|---|
| **Biomass left on site and ploughed on site** | | | |
| WLS | Woody biomass left on site | Biomass left at vegetation management location; natural decomposition | None |
| GLS | Grassy biomass left on site | Biomass left at vegetation management location; natural decomposition | None |
| GPoS | Grassy biomass ploughed on site | Biomass ploughed on fields to improve soil quality | None |
| **Grazing** | | | |
| GLG | Grassy biomass grazing large grazers | Vegetation management by year-round grazing, 70% cattle | Conventionally farmed cattle: grazers provide small amounts of organic meat |
| GGS | Grassy biomass grazing sheep | Vegetation management by herds of sheep | Conventionally farmed sheep: grazers provide small amounts of organic meat |
| **Energy production** | | | |
| WH | Woody biomass heat | Wood chip incineration producing heat | Conventionally produced heat |
| WCHP | Woody biomass CHP | Wood chip incineration producing heat and power in combined heat and power (CHP) plants | Conventionally produced heat and grid-electricity |
| GCHP | Grassy biomass CHP | Co-digestion of biomass with manure and subsequent CHP application of biogas | Conventionally produced heat and grid-electricity |
| GGG | Grassy biomass green gas | Co-digestion of biomass with manure and subsequent upgrading to green gas | Natural gas |
| **Material production** | | | |
| GCA | Grassy biomass composting for agriculture | Composting of biomass and application on agricultural fields to improve soil quality | Artificial fertilisers |
| GCG | Grassy biomass composting for growth media | Composting of biomass and use in production of growth media | Peat |
| GFo | Grassy biomass fodder | Ensilage of biomass and use as livestock fodder | Organic production grass |
| GFi | Grassy biomass fibres | Extraction of fibres and application in cardboard production | Pre-treated waste paper pulp |

### 6.2.2 Greenhouse gas emissions

The GHG emissions in kg $CO_2$-eq / tonne wet biomass ($t_{wb}$) of the different applications were calculated as the difference between emissions linked with the biomass application and avoided emissions of counterfactuals ($e_C$):

$$\varepsilon_{total} = \varepsilon_{VM} + \varepsilon_{T} + \varepsilon_{P} + \varepsilon_{B} + \varepsilon_{D} + \varepsilon_{R} - \varepsilon_{C} \quad (1)$$

Emissions of biomass applications included vegetation management activities ($e_{VM}$), transport of biomass to processing location ($e_T$), processing ($e_P$), biogenic $CO_2$ emissions ($e_B$), decomposition emissions ($e_D$) and ruminant $CH_4$ emissions ($e_R$). Input parameters for calculations were based on literature, data from Ecoinvent v3 LCI database using the IPCC 2013 GWP100a method [236], personal communication with stakeholders and own calculations. Default values for parameters for which ranges were found in literature were calculated as the geometric mean of all available data. For skewed distributions, as is the case for the applied input parameters, the geometric mean describes the central tendency of the data. Specific calculations for each application are shown in the Appendix (A2.). All input parameters and their sources are shown in Tables A1 and A2.

6

GHG emissions from vegetation management were calculated as:

$$\varepsilon_{VM} = \sum_{MU} HP \times F_{MU} \times E_{MU} \quad (2)$$

where *HP* is the harvesting pace for woody or grassy biomass (h / $t_{wb}$ harvested), $F_{MU}$ the fraction of machine use for each type of machine (dimensionless) and $E_{MU}$ the emission factors for each type of machine used (kg $CO_2$-eq. / h), including construction and fuel consumption. Data on machine use and fuel consumption were based on reports from contractors conducting vegetation management in the Netherlands (see A2 and Table A1).

Transport GHG emissions were calculated as:

$$\varepsilon_T = 2 \times TD \times E_T \quad (3)$$

where *TD* is the biomass transport distance (km) for each application and $E_T$ is the emission factor for transport with lorries (kg $CO_2$-eq. / tkm). $E_T$ is derived from

Ecoinvent and based on average load factors from the Tremove model v2.7b [237] and EcoTransIT [238] report. The emission is based on partial loading (83% of capacity) and empty return trips. The one-way transport distances were doubled to account for the distance covered by lorries to the floodplain and from the processing locations. For *TD* the minimum transport distance driving routes were determined for lorries to transport biomass from floodplains to biomass processing locations. In total, 95 processing locations in the Netherlands were identified from several sources (details in Table A3) and subsequently manually geocoded. Minimum transport distances for driving routes were calculated by means of the Google maps programming interface. The 179 floodplain sections in the study area, described in Section 6.2.3., provided the starting points and the 95 biomass processing locations gave the destination points, giving a total of 17,005 routes. Subsequently, the shortest route was selected for each floodplain section to each processing location with a specific biomass application (example shown in Figure 6.2). Transport distances were summarised by calculating the mean over all floodplain sections.

Processing GHG emissions were derived as:

$$\varepsilon_P = \sum_p A_p \times E_p \tag{4}$$

where $A_P$ is the amount of each product *P* produced (e.g. kg / $t_{wb}$ or MJ / $t_{wb}$) and $E_P$ is the emission factor for production of product *P* (e.g. kg $CO_2$-eq. / kg or kg $CO_2$-eq. / MJ). These emissions can include both upstream emissions (e.g. construction of processing installations) and processing emissions (e.g. energy consumption of processing installations and emissions occurring during processing), depending on the application (see A2).

Biogenic carbon emissions were derived as:

$$\varepsilon_B = E_B \times GWP_{bio} \tag{5}$$

where $E_B$ is the biogenic $CO_2$ emission of woody or grassy biomass (kg biogenic $CO_2$ / $t_{wb}$) and $GWP_{bio}$ the global warming potential of $CO_2$ emissions from biomass combustion (kg fossil $CO_2$-eq. / kg biogenic $CO_2$), as developed by Cherubini et al. [27]. A one-year rotation time was assumed for grassy biomass, based on the annual vegetation management required by flood safety regulations, resulting in a $GWP_{bio}$ and $e_B$ of zero for all grassy biomass applications. Rotation times for woody biomass vary according to location: five years for high flow zones and 20 years for low flow zones. The $GWP_{bio}$ of woody biomass was calculated based on the proportion of woody biomass increments in both flow zones, as described in Section 6.2.3.



Decomposition GHG emissions refer to:

$$\varepsilon_D = E_{N2O} \times GWP_{N2O} + E_{CH4} \times GWP_{CH4} \tag{6}$$

where $E_{N2O}$ and $E_{CH4}$ are $N_2O$ and $CH_4$ emissions occurring during natural decay of biomass (kg / $t_{wb}$) and $GWP_{N2O}$ and $GWP_{CH4}$ the global warming potentials of $N_2O$ and $CH_4$ (kg $CO_2$-eq. / kg $CH_4$). For woody biomass, $E_{N2O}$ and $E_{CH4}$ were calculated based on the fractions of N emitted as $N_2O$ and C as $CH_4$.

Ruminant emissions are equal to:

$$\varepsilon_R = E_R \times AR \div BMP_G \times 365\ days \times GWP_{CH4} \tag{7}$$

where $E_R$ are the ruminant $CH_4$ emissions of grazers (kg $CH_4$/ head /day), *AR* is the number of animals required to maintain one hectare for a year (head / ha), $BMP_G$ is the grassy biomass production per ha ($t_{wb}$ / ha) and the $GWP_{CH4}$ the global warming potential of $CH_4$ (kg $CO_2$-eq. / kg $CH_4$). The grassy biomass production per ha was calculated by dividing the grassy biomass produced in each section, as described in methods Section 6.2.3., by the surface areas of the same section. Subsequently, the average for all sections was calculated.

Counterfactual emissions were calculated as:

$$\varepsilon_C = \sum_C A_C \times E_C \tag{8}$$

where $A_C$ is the amount of each counterfactual *C* avoided (e.g. kg / $t_{wb}$) and $E_C$ is the emission of the production of each counterfactual (e.g. kg $CO_2$-eq. / kg). See appendix A2 for further details on the counterfactual GHG emission calculations.

### 6.2.3 Study area and biomass production

The overall climate mitigation potential of residual biomass was calculated over the terrestrial floodplain area of the three Rhine river distributaries in the Netherlands (Figure 6.2). The total embanked area amounts to 440 $km^2$, of which 62% is vegetated. Meadows dominate the land cover, but recent nature rehabilitation programmes have led to an increase in areas with herbaceous vegetation, shrubs and forests.

Biomass from publicly owned areas was distinguished from those that are owned privately. The public areas are managed by water management or other governmental organisations. These organisations are becoming increasingly interested in using landscape residues sustainably. Biomass from privately-owned areas was included to give an impression of the overall potential on a landscape scale.

The mean biomass production values per floodplain section were calculated based on three spatial datasets. Firstly, the entitled person per cadastral parcel [239] was classified as public, or private based on the name. Secondly, vegetation limitation data [218] divided the floodplain area into hydrodynamic flow zones defining the conveyance capacity. In high flow zones, the vegetation is limited to types with a low hydrodynamic roughness, e.g. meadows and agriculture. Shrubs, reeds and forests are allowed in low flow zones. Thirdly, ecotope data provided definitions for vegetation classes. Ecotopes are homogeneous landscape units based on specific hydro-morphological, geomorphological, ecological and land-use characteristics [240]. A schematic map of the 179 floodplain sections provided the spatial aggregation units (Figure 6.2). The biomass production was calculated according to Koopman et al. [222]. Four biomass production values were determined for each floodplain section using spatial overlays: (1) public-low flow, (2) public-high flow, (3) private-low flow and (4) private high flow. The four biomass production values were summed over all floodplain sections to determine the total biomass production for each combination in tonne dry matter (tDM). A final conversion was applied to wet biomass ($t_{wb}$) based on the dry matter (DM) fraction of woody and grassy biomass (Table A1).

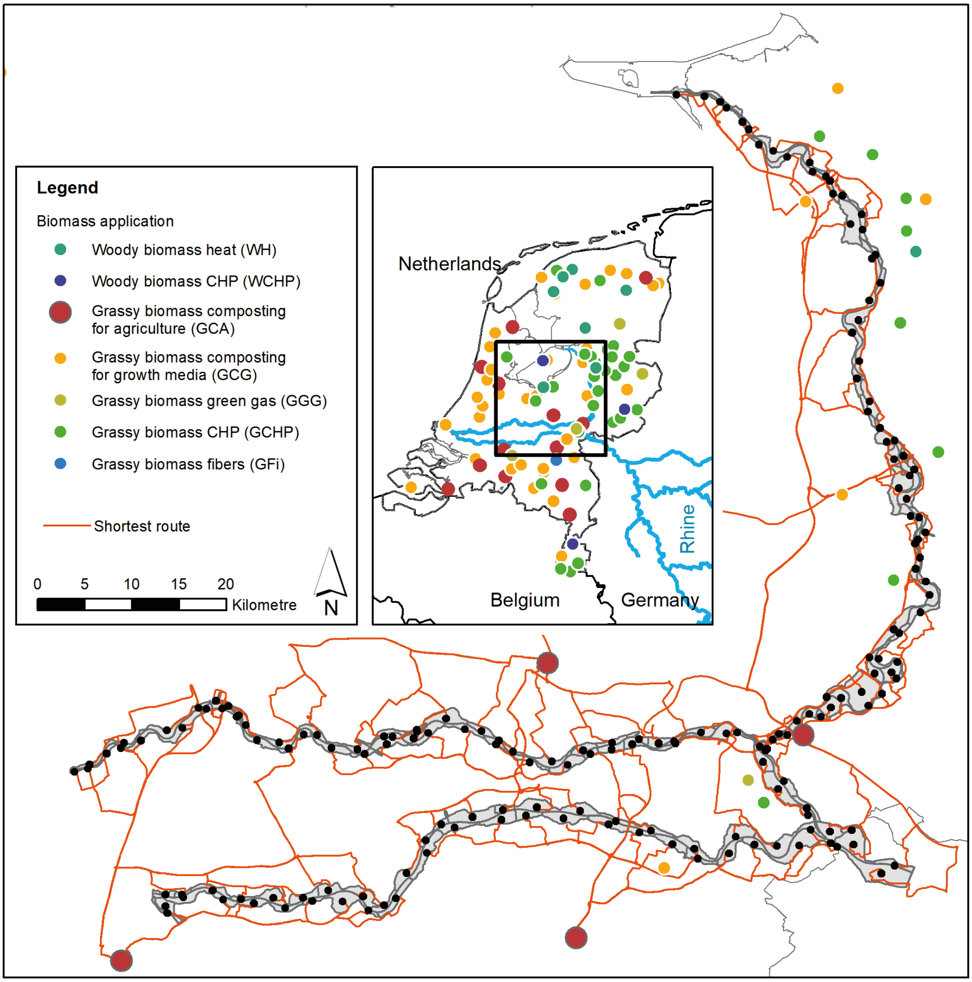


Figure 6.2 Schematic map of the study area. Showing the floodplain sections of the Dutch Rhine distributaries Waal, Nederrijn-Lek and IJssel (grey), the processing locations for different biomass applications and an example of the shortest driving routes between floodplains and grassy biomass composting sites for agriculture.

### 6.2.4 Sensitivity analysis

A sensitivity analysis on the GHG emissions of different biomass applications was performed. Table 6.2 shows the parameters analysed in the sensitivity analysis. Calculations and sources for all parameters are presented in Table A1. The total GHG emission in kg $CO_2$-eq. / $t_{wb}$ of each application was calculated separately for the default, minimum and maximum values of each parameter. The resulting GHG emission outcomes were then plotted against the parameter variation expressed as a percentage, where the default represents 100%.

Table 6.2 Parameters analysed during sensitivity analysis. *For each parameter, the use in the equations presented in Section 6.2.2 and the default value used in the calculation is shown, together with the minimum and maximum value used during the sensitivity analysis. Calculations and sources for all parameter values can be found in Table A1.*

| | Parameter | Equation | Unit | Default value | Minimum value | Maximum value |
|---|---|---|---|---|---|---|
| 1. | Harvesting pace woody biomass | (2); *HP* | h / $t_{wb}$ harvested | 0.91 | 0.31 | 2.67 |
| | Harvesting pace grassy biomass | (2); *HP* | h / $t_{wb}$ harvested | 0.57 | 0.42 | 0.77 |
| 2. | Biomass transport distance | (3); *TD* | km | Table A1 | 50% of default | 200% of default |
| 3. | Ploughing required for GPoS | (4); part of $A_P$ | ha / $t_{wb}$ | 0.2 | 50% of default | 200% of default |
| 4. | Biogas yield during co-digestion | (4); part of $A_P$ | $m^3$ / $t_{wb}$ | 70.2 | 60 | 77 |
| 5. | Calorific value woody biomass (as received) | (4); part of $A_P$<br>(8); part of $A_C$ | MJ / $t_{wb}$ | 8030 | 7400 | 10120 |
| 6. | WCHP electric conversion efficiency | (4); part of $A_P$<br>(8); part of $A_C$ | dimensionless | 0.16 | 0.16 | 0.3 |
| 7. | $CH_4$ emissions of WLS decomposition; fraction of C emitted as $CH_4$ | (6); part of $E_{CH4}$ | dimensionless | 0.01 | 0.01 | 0.022 |
| | $N_2O$ emissions of WLS decomposition; fraction of N emitted as $N_2O$ | (6); part of $E_{N2O}$ | dimensionless | 0.01 | 0.01 | 0.016 |
| | $N_2O$ emissions of GLS and GPoS decomposition | (6); $E_{N2O}$ | kg $N_2O$ / $t_{wb}$ | 0.07 | 50% of default | 200% of default |
| 8. | $CH_4$ emissions per sheep | (7); $E_R$ | kg $CH_4$ / grazer / d | 0.019 | 0.014 | 0.024 |
| | $CH_4$ emissions per large grazer | (7); $E_R$ | kg $CH_4$ / grazer / d | 0.19 | 0.13 | 0.27 |
| | Sheep required to maintain one ha | (7); *AR* | grazers / ha | 5.24 | 3.79 | 7.22 |
| | Large grazers required to maintain one ha | (7); *AR* | grazers / ha | 1.41 | 0.4 | 2 |
| 9. | Fertiliser replacement of GCA | (8); part of $A_C$ | kg N/ $t_{wb}$ | 0.89 | 0.5 | 1.92 |

*table continues*

| | Parameter | Equation | Unit | Default value | Minimum value | Maximum value |
|---|---|---|---|---|---|---|
| 10. | GHG emissions of GCG counterfactual growth media from peat | (8); $E_c$ | kg $CO_2$-eq. / t peat | 811.4 | 550 | 1197 |
| | Peat replacement of GCG | (8); part of $A_c$ | t peat / t compost | 0.67 | 0.2 | 1 |
| 11. | GHG emissions of GFi counterfactual fibre from waste paper | (8); $E_c$ | kg $CO_2$-eq. / t paper pulp | 211.2 | 134.14 | 298.64 |
| 12. | GHG-intensity of counterfactual electricity WCHP and GCHP | (8); part of $E_c$ | kg $CO_2$-eq. / MJ | 0.15 | 0.12 | 0.29 |



The sensitivity of the following parameters was considered:

1. The harvesting pace of both woody and grassy biomass shows large variations in literature and has a large influence on harvesting emissions, which are part of almost all applications.
2. Biomass transport distances were based on the current minimum distance between floodplains and processing locations, as described in Section 6.2.2. Distances could change when roads or processing locations are altered or added. Variations of a factor 0.5 and 2 were investigated.
3. The ploughing required to apply one tonne of wet biomass on agricultural soils has a large variability in practice and documentation is limited. Variations of a factor 0.5 and 2 were explored.
4. Biogas yields during co-digestion of grassy biomass strongly influence results and are variable due to different feedstock mixtures and fermenter conditions.
5. The calorific value of wood varies with moisture content, which depends on field and (passive) drying conditions. Calorific values for 40-50% moisture contents were analysed.
6. The default electric conversion efficiency of woody biomass CHP installations is based on the current situation. However, larger-scale electricity production can result in higher efficiencies and greater avoided emissions. A scenario of CHP with higher electricity output and higher efficiency was explored.
7. $CH_4$ and $N_2O$ emissions relating to natural decomposition of biomass are highly variable and little data is available. Because this study considered non-piled wood with aerobic decomposition, default woody biomass decomposition emissions were based on minimum emissions of piled wood. This assumption was tested

by applying a typical value for piled wood as a maximum value. Similar variation is expected for decomposition of grassy biomass (GLS and GPoS). Variations of a factor of 0.5 and 2 were investigated.

8. Both the number of grazers required to maintain one ha of land and the $CH_4$ emissions per grazer affect the GHG emissions and have a substantial natural variability. The maximum and minimum calculated for the parameter based on different sources was analysed.
9. Large variability was observed in literature for data concerning N fertiliser replacement of compost, so the overall range described by different sources was analysed.
10. Regarding GCG, large variations were described in literature for both the amount of peat replaced per t compost and the GHG emissions of the counterfactual (growth media produced using peat). Both are influential parameters.
11. The GHG emission of the GFi counterfactual (fibre produced from waste paper) is uncertain due to lack of data. The actual GHG emissions of fibre production (including waste paper collection, sorting and re-pulping) are unknown. The GHG emission of recycled paper minus the electricity for the papermaking step was used but this could be a conservative estimate. The geomean of both parameters was used as default value and the overall range of values was explored here.
12. The WCHP and GCHP counterfactuals apply the current state of grid-electricity in the Netherlands. Changes in avoided emissions were quantified by applying gas electricity (minimum value) and coal electricity (maximum value), rather than the Dutch grid mix (default).

## 6.3 Results

### 6.3.1 Greenhouse gas emissions and savings of current residual biomass applications

Figure 6.3 shows the GHG emissions and savings for each application in kg $CO_2$-eq. / $t_{wb}$ and the total net GHG emissions, representing the overall GHG burden or benefit that can be achieved with each tonne of residual biomass. Biomass left or ploughed on site and biomass removal by grazing animals both result in net GHG burdens. All energy applications provide GHG benefits, ranging from -132 to -112 kg $CO_2$-eq. / $t_{wb}$ for woody biomass (WH and WCHP), and from -56 to -0.5 kg $CO_2$-eq. / $t_{wb}$ for grassy biomass (GCHP and GGG). Note that the conversion of biogas to green gas, which more than doubles the processing emission, appeared not to be particularly worthwhile from a GHG perspective because the use of biogas in CHP installations achieves much higher GHG benefits. Material applications of grassy biomass for fibre and fodder achieve GHG benefits of -43 and -3 kg $CO_2$-eq. / $t_{wb}$. Depending on the final product, composting results in both the greatest GHG benefit and the highest GHG burden for grassy biomass with values of -229 and 62 kg $CO_2$-eq. / $t_{wb}$ (GCG and GCA). This is mainly due to the large difference in counterfactual emissions. Replacing peat in growth media with compost achieves great GHG benefits. Applying compost in agriculture replaces only moderate amounts of fertilisers, which results in small GHG savings from avoided fertiliser production and application. In practice, each tonne of biomass delivered to a composting installation will contribute to both products. Assuming 18% GCG and 82% GCA application [based on 241], the combined outcome will be 9 kg $CO_2$-eq. / $t_{wb}$. Biogenic $CO_2$ emissions contribute significantly to woody biomass application emissions, averaging 40%. Transport and vegetation management emissions each contribute an average of 21% to all applications featuring these emissions.

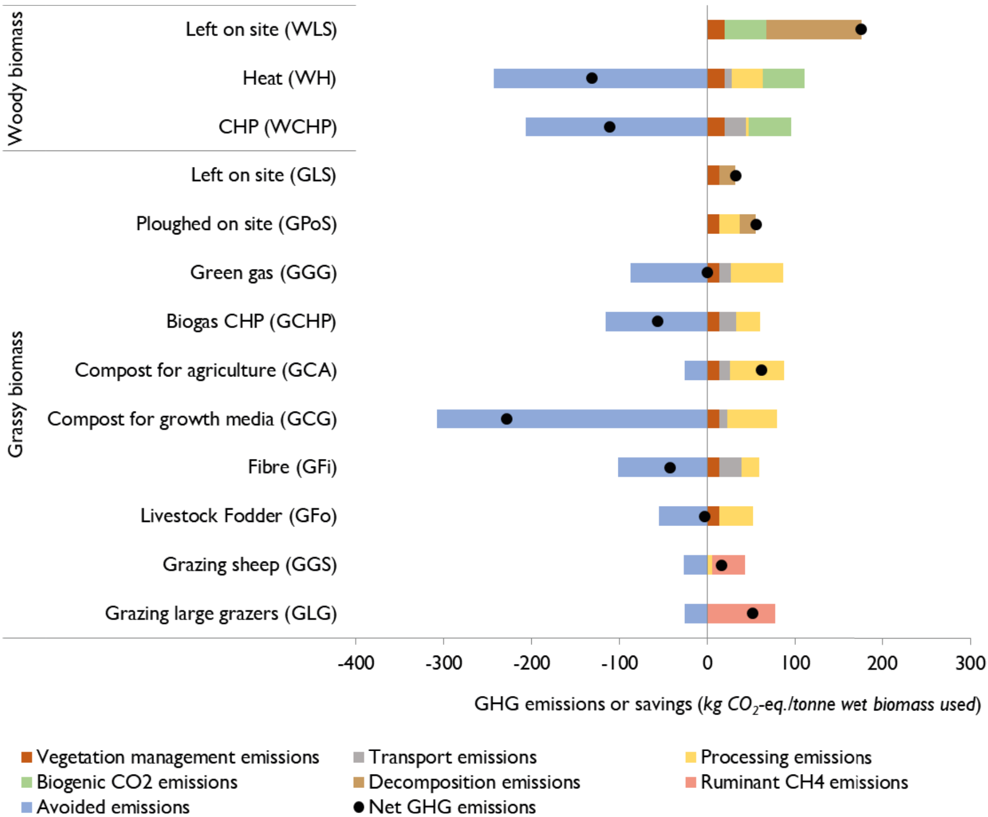


Figure 6.3 GHG emissions and savings of current residual biomass applications at biomass scale. GHG emissions from various sources are presented as positive values. GHG savings, achieved through the replacement of counterfactuals, are presented as negative values. Net GHG emissions are the sum of emissions and savings and are presented as black dots.

### 6.3.2 Climate change mitigation potential of residual biomass use

The overall potential for residual biomass derived from the Rhine floodplains to contribute to climate change mitigation differed widely (Figure 6.4). It was calculated that 49 and 93 kilotons (kt) of woody biomass, and 322 and 583 kt of grassy biomass are produced per year on publicly-owned areas and over the whole study area. 86% of all residual biomass is grassy biomass and as a result, grassy biomass applications with overall GHG benefits achieve a higher climate change mitigation potential in comparison to woody biomass applications at landscape scale.

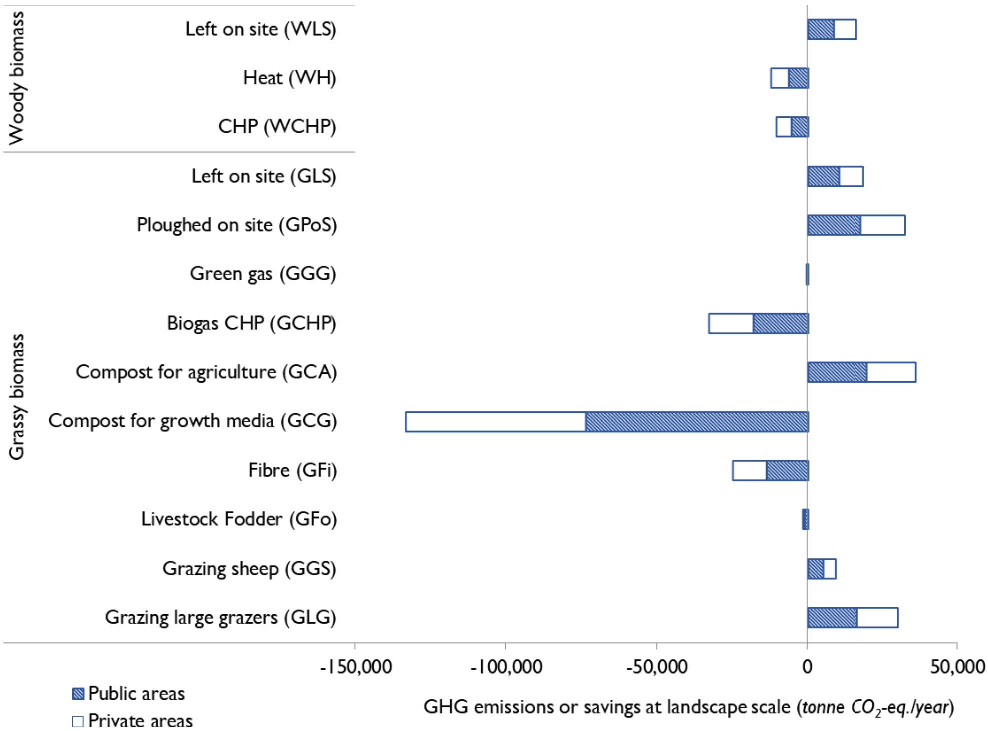


Figure 6.4 GHG emissions and savings of current residual biomass applications at landscape scale. The total GHG emissions or savings of each application, multiplied with the biomass available in the study area (cf. Figure 6.2) each year are shown. Biomass availability from publicly and privately-owned areas was distinguished which together represent the entire study area.

The overall climate change mitigation potential depends not only on the amount of GHG emissions saved by beneficial applications, but also on their processing capacities. Table 6.3 shows the current processing capacities of the five applications resulting in clear GHG savings and the overall potential for processing biomass from the study area, based on a combination of the current capacity and the available residual biomass in the study area. Constraints resulting from current workload of these installations are not considered, assuming in the future additional capacity could be added if more landscape residues were to be processed. Table 6.3 shows that the total amount of residual grassy and woody biomass available annually would not exceed the maximum processing capacity of the most GHG-beneficial applications, WH and GCG. If public organisations ensured that their biomass was processed for the most GHG beneficial applications, a maximum contribution to climate change mitigation of 6.4 and 73.6 kt $CO_2$-eq. / y could be achieved for woody and grassy biomass. If all biomass from the whole study area were applied for the most GHG beneficial applications, a maximum saving of 145 kt $CO_2$-eq. / y could be achieved.

Table 6.3 Current processing capacities of the five applications with clear GHG savings in the Netherlands. Capacities are based on data from existing installations, see Table A3. The potential to process biomass from the study area is based on a combination of the current capacity of the applications and the available residual biomass in the study area. The lowest of these values defines the potential to process. The last two columns show the maximum product output from the study area and a comparison with reference markets.

| Application | Current capacity in kt wet biomass / y | Potential to process biomass from study area in kt wet biomass / y | Maximum product output | Market comparison of maximum product output |
|---|---|---|---|---|
| WH | 141[a] | 93 | 674 $TJ_{th}$ / y | 16,042 Dutch households[e] |
| WCHP | 57[a] | 57 | 25 $TJ_{el}$ / y | 2,323 Dutch households[e] |
| | | | 242 $TJ_{th}$ / y | 5,762 Dutch households[e] |
| GCG | 642[c] | 583 | 218 kt peat replacement / y | 91% of peat in growth media production in NL[c] |
| GCHP | 14[b] | 14 | 8 $TJ_{el}$ / y | 790 Dutch households[e] |
| | | | 12 $TJ_{th}$ / y | 290 Dutch households[e] |
| GFi | 60[d] | 60 | 29 kt fibre / y | 0.5% of recycled paper use in NL[f] |

[a] Calculation based on the identified processing locations (described in Table A3) and data from RVO [242]

[b] Calculation based on data from personal communication with several companies running biogas CHPs

[c] Calculation based on market data from BVOR [241]

[d] Calculation based on data from personal communication with a grass fibre producing company

[e] Calculation based on household energy consumption data from milieu centraal [243]

[f] Calculation based on data on recycled paper products in the Netherlands [244], assuming 1 tDM fibre replaces 1 t of recycled paper

These maximum savings are based on the usage of all available woody and grassy biomass for the most GHG-beneficial applications at their maximum processing capacities. A comparison of applications featuring the highest GHG benefits with those with the highest GHG burdens reveals a difference of 15.0 kt $CO_2$-eq. / y for woody biomass and 28.5 kt $CO_2$-eq. / y for grassy biomass from publicly-owned areas and 93.5 and 169 kt $CO_2$-eq. / y for the whole study area.

Table 6.3 shows that WH has the highest potential product output of all energy applications despite the limited availability of wood. WCHP and GCHP are limited by current processing capacity because there are only few WCHP installations and most biogas installations are not equipped to process grass as a co-product. Potential for GCG is large, but the large volumes of garden and kitchen wastes currently processed will limit the capacity to process landscape residues in practice.



### 6.3.3 Sensitivity to parameter variability and data uncertainties

The sensitivity analysis (Figure 6.5) shows that the results of this study are robust, except in four cases where a relatively large sensitivity is observed. Firstly, GHG emissions from biomass decomposition are highly sensitive to the share of decomposition taking place under anaerobic conditions, releasing $CH_4$. Under maximum anaerobic conditions, woody biomass decomposition (WLS) could lead to 67% higher overall GHG emissions per tonne of biomass (Figure 6.5a). Grassy biomass is thinner and more spread out, and is assumed to decompose aerobically. Secondly, CHP applications are sensitive to CHP efficiency and the level of GHG emissions of the counterfactual electricity production (Figure 6.5b). When replacing coal-based electricity rather than replacing the default counterfactual (current Dutch grid electricity mix) GHG emission savings increase by 44% and 54% for grassy (GCHP) and woody biomass (WCHP). For WCHP, higher efficiencies achieved through upscaling could double GHG emission savings. Thirdly, while the variability in calorific value of wood is low (the minimum value is 8% lower than the default, the maximum value is 26% higher), it is highly influential on GHG emissions of WH and WCHP: dryer wood can increase emission savings by 40% (Figure 6.5b). Fourthly, net GHG emission savings of GCG are sensitive to the amount of peat replaced and to the GHG-intensity of the replaced peat (Figure 6.5c), both of which are uncertain. GHG savings could be 67% larger, but also strongly reduced. It is unlikely that GHG savings would become smaller than those of other investigated grassy biomass applications.

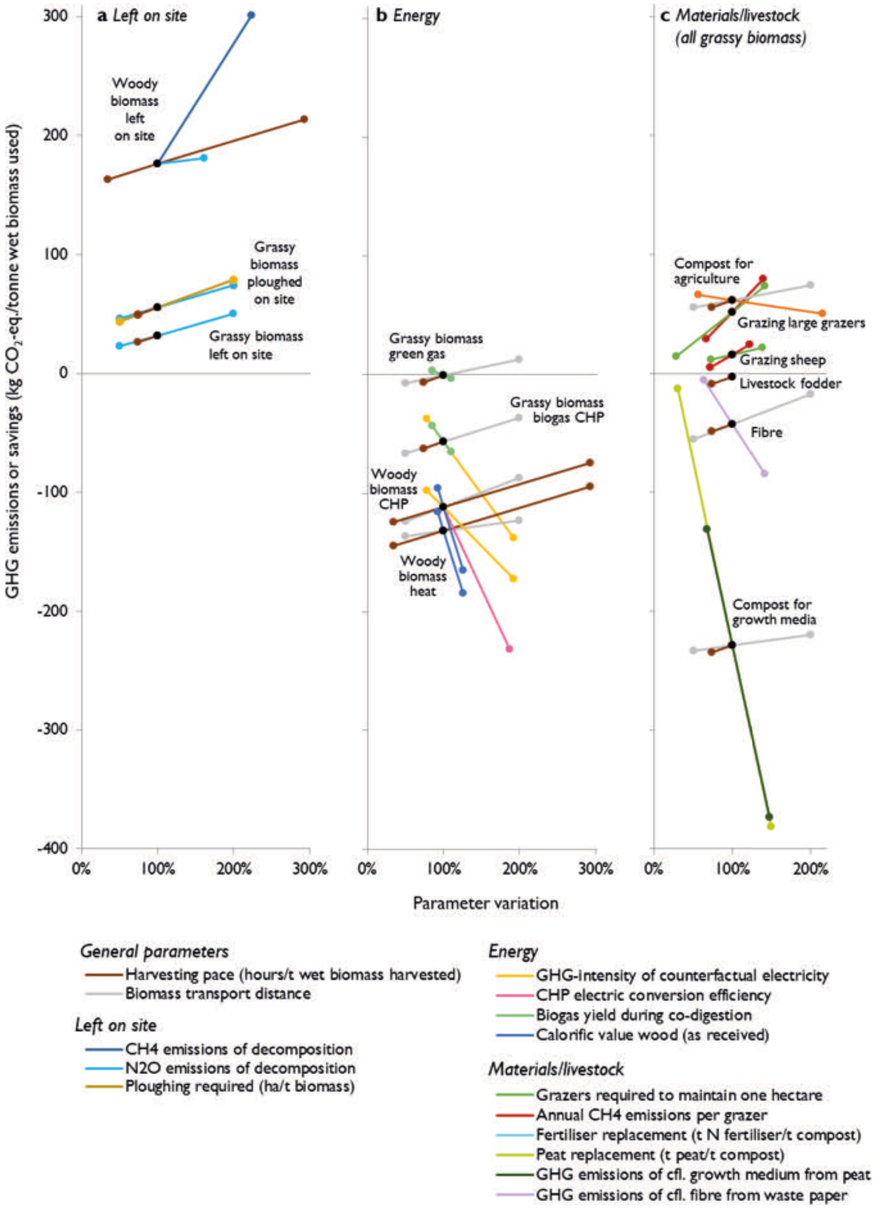


Figure 6.5 Sensitivity analysis of total GHG emissions of residual biomass applications. Sensitivity to parameter variations is shown based on the percentage of change in the parameter range (x-axis) and the related GHG emissions or savings (y-axis). Parameter ranges are presented in Table 6.2.

The sensitivity of the results to variation in other parameters is more limited. Harvesting pace and transport distance can for instance vary substantially (200-300%), but change overall emissions per $t_{wb}$ by less than 30%. Only one application, GGG, may alter from slightly GHG-beneficial to a small GHG burden when transport distance increases. The number of grazers and their enteric $CH_4$ emissions have a natural variability which affects the net GHG emissions of the grazing applications to a larger degree. Even when considering this variation, net GHG emissions remain relatively stable compared to other applications (Figure 6.5c).



## 6.4 Discussion

This study compared the GHG emissions of different applications of residual biomass released during landscape management and provided relevant information on the overall climate change mitigation potential of residual biomass. The approach presented facilitated a comparison between a variety of both energy and material biomass applications through the consideration of counterfactuals. The sensitivity analysis showed that, although variation in some parameters may influence the GHG outcome, the calculated GHG benefits or burdens of applications are robust.

Higher GHG benefits were found for bioenergy than for biomaterials, an observation also described by Hanssen et al. [49] for woody biomass. An exception is the replacement of peat as a growth medium, which results in large $CH_4$ emissions. Other authors have applied approaches similar to the comparison with counterfactuals in this study. These authors consider the indirect effects of products and often focus on fossil fuel replacement. For example, How et al. [245] developed a simplified optimisation method for selecting processing technology and transport designs for residual biomass, including the replacement of fossil fuels in their environmental impact assessment. Similarly, Čuček et al. [246] developed an approach to optimise supply chains considering various footprints and analyse the bioenergy applications of different biomass resources by considering the indirect effect of replacing fossil energy. These studies describe methodologies for the optimisation of supply chains in established biomass applications with the aim of maximising profits while minimising environmental impacts.

The current study provides a novel comparison of currently feasible and practiced applications, highlighting the environmental impacts of using a particular set of biomass resources.

Two earlier publications reported the impacts of applications using residual biomass from landscape management in riverine areas. Recchia et al. [230] analysed the environmental benefits of energy derived from riparian vegetation. These authors conducted a lifecycle analysis on woody biomass burnt in a 300kW heat boiler reporting $CO_2$-eq. emission reductions of between 78 and 83% in comparison with fossil energy production from natural gas. This type of energy generation is similar to the WH application in the current study, which would result in an equivalent 54% emission reduction. It should be noted that Recchia et al. [230] did not include biogenic $CO_2$ emissions in their analysis, while it accounted for 40% of emissions in this study ($e_B$, based on $GWP_{bio}$). Excluding $e_B$ from the current calculations results in a reduction of 74%, which is close to the range described by Recchia et al. [230], demonstrating the importance of considering biogenic $CO_2$ emissions. Other differences are the assumed transport distance and harvesting machinery, and the use of a different LCI database. Differences in harvesting machinery parameters are due to different landscape characteristics of the study area (mainly woody biomass as opposed to mostly grassy biomass in the current study). Boscaro et al. [231] analysed the GHG impacts of grass obtained from riverbank landscape management in biogas production. The authors calculated the GHG balance as the difference between the emissions of biogas production from grass and the fossil fuel emissions saved as a result of heat and electricity production with biogas. This is comparable to the GCHP application. The authors calculated GHG savings of between -67 and -86 kg $CO_2$-eq. / $t_{wb}$, based on different harvesting practices and logistical scenarios, both of which differed from the approach presented in this study. When using their reported transport distances of 5 and 10 km in the current calculations, emissions of -74 kg and -73 $CO_2$-eq. / $t_{wb}$ result, which fall well within the range reported by Boscaro et al. [231].

The contribution that residual biomass from vegetation management in river floodplains makes to climate change mitigation is an important ecosystem service [222], but this residual biomass can also provide other services. Some of the applications discussed in this paper may have costs or benefits other than their GHG impact which may play a role in choosing a particular biomass application. Natural vegetation management with grazing animals, for example, may also provide cultural ecosystem services [247] and contribute to biodiversity recovery during river restoration [248]. Removal of biomass for applications outside of the riparian area may result in carbon and nutrient losses. Carbon sources remain and decompose slowly under natural conditions but certain management practices result in their active removal and a rapid release of $CO_2$. This has been described as a potentially problematic aspect in the harvest of stumps and logging residues [249], whole tree harvesting practices [226] and the removal of crop residues [250]. Leaving at least a part of the biomass on site may be advantageous for soil quality under certain conditions but is not always feasible due to flood safety regulations and disadvantageous from a GHG perspective. GCA demonstrated the highest GHG burden but can contribute to an increase in the organic matter content of agricultural soils. Soil quality is becoming increasingly important due to ongoing soil depletion in agriculture. Other factors may influence the choice of biomass applications and ideal combinations based on net GHG benefits alone may not be feasible in practice. For example, composting depends on inputs of woody biomass. The compost mixture would be too dense if only grassy biomass were composted, hindering aerobic processing. In practice, it may not be realistic to apply only residual woody biomass for energy production and only grassy biomass for composting to provide growth media.



Results of this study are based on calculations using carefully selected parameters. Limitations result from lack of data and simplifications which could be specified further in future research. For example, transport emissions could be specified considering optimisation under capacity constraints [251] and current workload of processing installations could be analysed to further define maximum current processing capacities. Future research could also extend to analysing additional impacts other than GHG emissions and compare new applications that are currently under development.

## 6.5 Conclusion

Removal and application of landscape biomass can contribute to climate change mitigation if GHG beneficial applications are chosen. This is true if landscape biomass can be removed without negative ecological consequences or has to be removed for other reasons, for example where riparian vegetation is removed to reduce flood risk. Producing heat or combined heat and power from woody biomass and growth media from compost of grassy biomass achieve the greatest GHG benefits, although the impact of growth media from compost is uncertain. Several other applications demonstrate GHG burdens and should be avoided from a climate change perspective. In current river management practice the choice between different residual biomass applications depends on various factors including price, contribution to different ecosystem services, processing capacities of applications, and actors responsible for vegetation management (water management organisations, contractors or private land owners). It is essential that GHG benefits and burdens of different applications and their counterfactuals are considered to ensure that residual biomass makes a positive contribution to climate change mitigation.

**Vegetation in riverine landscape (S. Pfau)**

# Chapter 7

## Synthesis

Using biomass as a natural resource to replace fossil resources in the production of energy and materials is a promising way to make a 'green choice', reducing negative consequences of our consumption behaviour. But biomass use is not undisputed, as not all biomass is produced sustainably and biomass applications do not automatically contribute to a sustainable future. A true 'green choice' would therefore also involve choosing to use sustainably produced biomass or residual biomass and making an informed choice between applications, considering their contribution to sustainability. The research reported in this thesis explored the relationship between sustainability and the bioeconomy. It describes the scientific discussion surrounding this relationship and reveals a variety of factors influencing the sustainability of biomass use. A variety of insights related to the choice of biomass resources and the choice between applications are provided. Furthermore, it highlights opportunities and constraints surrounding these choices, stemming from policies and current practice. In the following sections of this synthesis, the issues related to making a green choice introduced in Section 1.4 are revisited, presenting concluding remarks based on the findings from all chapters and discussing important trends and current developments. Subsequently, the methodological choices made during this research are reflected upon. Finally, recommendations for further research based on the insights from this thesis are listed.

## 7.1 Development of biomass use and the bioeconomy

### 7.1.1 Drivers of the bioeconomy

The bioeconomy concept promises to contribute to a sustainable future if biomass is chosen as a resource instead of fossil resources. This is often how the bioeconomy is approached in both scientific literature (Chapter 2) and by stakeholders (Chapter 5). The bioeconomy is expected to aim at increased sustainability, and bio-based energy and products are assumed to be more environmentally friendly than fossil-based products. But even though sustainability is considered as important goal and context of the bioeconomy, it is only one of various drivers behind its development (Chapter 2). The most important drivers are to reduce dependence on fossil fuels and to reduce GHG emissions, in reaction to reduced availability of fossil resources, with more effort required to obtain them and complicated international relationships with fossil-rich regions, and the consequences of decades of GHG emissions from fossil fuel use. Additionally, other positive expectations further drive the development of the bioeconomy, including a boost to rural areas, secure supply of energy and commodities and expected economic benefits.



### 7.1.2 History of biomass use

Historically, biomass has always been an important resource and the bioeconomy concept can be seen as a rediscovery of this importance, in reaction to negative consequences of fossil resource use (Chapter 4). Biomass has always been the primary resource for mankind, providing food, energy and materials. But use of biomass has changed drastically in the course of the last centuries. The demand for biomass for non-food applications has undergone several changes. Before the industrial revolution, demand rose to produce increasing amounts of energy. But during the industrial revolution and the rise of petrochemicals about a century later, the primary input for energy and material production changed from biomass to fossil resources. The current bioeconomy presents a switch back to biomass and again increases demand. Sourcing of biomass has changed from harvesting of naturally growing biomass to increasingly advanced agriculture, forestry and crop manipulation. Applications have diversified from simple bioenergy and material uses such as firewood and construction with wood and straw, to high-tech energy carriers and materials, such as biofuels and bioplastics.

### 7.1.3 Bioeconomy and sustainability

The increasing demand for biomass endangers sustainable supply in the future. Before the industrial revolution, limited supply of wood constrained economic growth, as energy demands surpassed what could be supplied sustainably (Chapter 4). Returning to biomass as main resource for industrial production now is problematic, as current demands for energy and consumer goods are higher than ever. While sustainability is considered an important goal of the bioeconomy (Chapter 2), this same goal may be endangered by overuse of biomass to fulfil all demands. This thesis points out various potential consequences of increased biomass use, such as land-use change and related emissions and loss of ecosystems (Chapters 1, 2 and 4). In the scientific literature, majority of papers consider the relationship between bioeconomy and sustainability as generally positive, but also acknowledges problems, such as competition for land-use, resulting in land-use change and competition with other land-based products (Chapter 2). Most publications discuss conditions and possible interventions for these problems, for example sustainable production systems (referring to both biomass production and supply chains of bio-based products) and efficient biomass use (for example using all parts of crops, valorising all components of biomass and choosing the best application for each amount of biomass). Strategies for sustainable resource supply that are frequently referred to are cultivating biomass on marginal land and using residual biomass.

### 7.1.4 Bioeconomy and circular economy

Next to the development of the bioeconomy, other concepts responding to current sustainability challenges are also gaining importance. The circular economy is closely related to the bioeconomy. It aims at moving away from a linear economy (take, make, dispose) towards a new economic model where economic development is decoupled from finite resource consumption [252]. Biological cycles play a crucial part in the circular economy: biomass as a renewable, non-finite resource serves as input for supply chains. It forms the largest circle of material recycling: $CO_2$ released during material degradation is taken up and transformed into new material by plants during photosynthesis. Use of residual biomass links up well with the circular economy concept, as it reduces waste and primary material demand (Chapter 4). The circular economy concept aims at, for example, designing out waste from production systems, avoiding the degradation of natural capital and developing alternative business models based on services rather than owning products [252]. But a great variety of definitions are in use and it has been shown that while the primary assumption is that sustainability is at its centre, the main aim of the circular economy seems to be economic prosperity, followed by environmental quality [253]. It is also criticised that social and societal challenges, which are also part of sustainability, are underrepresented [253,254]. Neither the bioeconomy nor the circular economy concept appear to be flawless ways to approach a more sustainable future. In the circular economy, attention for ecological sustainability may be second place to economic prosperity and attention for new business models. In the bioeconomy concept, there is little attention for reducing or avoiding consumption, as the main approach is to replace resources. This is equivalent to the largest circle of material recycling in the circular economy, but may not be the most efficient way of recycling. More consideration should go into the consolidation of the bioeconomy and circular economy concepts, determining which strategy is best to achieve increased sustainability in which situation.



#### 7.1.5 Conclusion: Sustainability as central goal

The results from this thesis show that choosing biomass instead of fossil resources does not necessarily contribute to sustainability. Choice of resources and applications are crucial. On the way to sustainability, the bioeconomy and circular economy concepts both can play an important role. But this thesis shows that sustainability should be a central goal and consideration, if these concepts are to contribute to a more sustainable future.

### 7.2 Sustainable biomass resources

#### 7.2.1 Choice of biomass resources

As demand for biomass rises with the development of the bioeconomy, the choice of sustainable resources becomes crucial. This thesis outlined various sustainability challenges of cultivated biomass (Chapters 1, 2 and 4). Crop production for biofuels and materials can, for example, result in deforestation to create new arable land or competition with other land-uses. Use of woody biomass from forestry is debated to result in large carbon emissions on the short term, counteracting the efforts to mitigate climate change through renewable energy production. The consideration of biogenic $CO_2$ emissions was found to be significant in Chapter 6. To avoid these challenges, two strategies are often suggested: production of biomass on marginal lands and the use of residual biomass (Chapter 2). Other second generation biomass feedstocks also include lignocellulosic biomass and algae biomass [34]. Plantations on marginal lands are argued to avoid competition for arable land. While food and feed production usually require high soil qualities, biomass production for energy and material applications is possible on less attractive lands. However, investment costs are high and potential returns low [140], and repurposing previously unused land for crop production threatens biodiversity and ecosystem services provided by the natural vegetation [120]. Use of residual biomass is considered because it makes it possible to re-use materials that would otherwise be waste as input for new production chains (Chapter 2).

### 7.2.2 Advantages and challenges of residual biomass

Using residual biomass offers several sustainability advantages (Chapter 4), including forgoing land-use change, reducing waste and increasing the overall efficiency of resource use. Challenges of residual biomass use include spatial availability, as they are usually by-products of other processes, a lower quality due to high heterogeneity and negative impacts related to changing the use of the resource. Chapter 4 describes current functions of residual biomass and possible consequences of resource use change. The extraction of crop or forestry residues that are usually ploughed back into fields or left behind on the forest floor, for example, can lead to soil degradation. Residual biomass requires different considerations than cultivated biomass: instead of the land, the resource already has a function and resource use change has consequences. Various factors should be considered to evaluate potential uses of residual biomass, including the potential to reduce GHG emissions, replace fossil resources, mitigate disturbance of biogeochemical flows and produce environmentally friendly products. Chapter 6 presents a comparison of 13 applications of two types of residual biomass, focussing on GHG emissions. It considers both current uses and functions and new applications, comparing them with one another but also with conventional counterfactuals. The results show the importance of taking counterfactuals into account and analysing not only new applications, but also the current uses they may replace.

### 7.2.3 Residual biomass in practice

Chapters 3 and 5 analysed the use of residual biomass in practice, exploring different sectors: Chapter 3 focussed on application of residual biomass in biogas production and its respective use in different sectors, while Chapter 5 analysed the change of perspective in public organisations owning residual biomass. Both chapters show that in practice the value of residual biomass is a very influential factor in the choice for residual biomass over cultivated biomass. Bioenergy producers are increasingly interested in less attractive, less readily available and difficult to process biomass, including many residual biomass sources (Chapter 3). However, this is not due to the fact that residual biomass is considered more sustainable, but that it is usually cheaper. Contrastingly, biomass owners expect the value of residual biomass to increase in the future (Chapter 5). They expect that the bioeconomy will gain importance and demand for biomass will rise, as well as technical possibilities to use lower-value biomass. These expectations are in conflict with one another. Based on the results of this study, it can be concluded that residual biomass will probably not increase much in value in the near future. Residual biomass is often already used for something and thus not without value in practice. For the value to rise, others would have to be willing to pay more. But producers of bioenergy and bio-based products not only compete with one another and other biomass uses over resources, they also compete with fossil-based products over the prices of end products. Trying to compete with these conventional products, they strive to improve their business case by choosing cheaper residual biomass. Consequently, they cannot pay more for residual biomass, as this weakens their competitive position on the consumer market. Even if bio-based options become far more attractive in comparison to conventional products than they are now, residual biomass resources are often heterogeneous and of low quality, requiring more intensive (and expensive) pre-treatments than more expensive biomass sources. Finally, if the demand for biomass and with it its value would increase in the future, provision of biomass would become more lucrative. Residual biomass is only a by-product of other processes, and the disadvantages described in Chapter 4, especially related to spatial availability and accessibility, mean that its provision cannot easily be scaled up efficiently.

### 7.2.4 Conclusion: Opportunities of residual biomass

Residual biomass can be a sustainable alternative to cultivated biomass, but it is not usually without function and the impact of choosing a different application should be evaluated and considered in decision making. As residual biomass is a by-product of other processes and its provision cannot be scaled up easily, it is preferable to look at its use from a resource perspective, rather than from an application perspective: where residual biomass is available and can potentially provide greater societal value than traditional uses or functions, it is useful to compare new applications. It may be appropriate to change processes in a way that allow for an optimised use of the residues, for example by changing harvesting practices or waste collection.

## 7.3 Biomass applications and consequences of biomass use

### 7.3.1 Applications of residual biomass

Residual biomass is used in various applications. In this thesis, several uses of residual biomass from landscape management in riverine areas have been described (Chapters 5 and 6). These include bioenergy and bio-based products, as introduced in Chapter 1, but also more traditional uses or functions of biomass. In energy production, residual biomass is used for example for heat or electricity production from wood chips and biogas or green gas production from grass and manure. In material production, woody biomass is used for construction and grassy biomass for compost, fodder and fibres. More traditionally, residual biomass is left on site or ploughed into the field, or it is removed by grazing animals. An interesting link between bioenergy and bio-based products is the production of biogas, which can serve as an energy source, but can also be applied as resource in the chemical industry (Chapter 3). Biogas is a versatile energy source and can fulfil the role of a system service provider in the energy system, but it can also contribute to the bioeconomy as a way to use low-value biomass and by-products.

### 7.3.2 Evaluation of efficiency

The choice of application influences how much biomass use contributes to sustainability. An important aspect of this choice is an evaluation of the efficiency of biomass use, as this is often used to reason the choice of an application or prioritisation between applications. Concepts to increase the efficiency of biomass use include biorefineries, cascading principles and prioritisation according to the value of end products (Chapters 3, 4 and 5). Biorefineries aim at separating and using as many components of biomass resources as possible, usually for different applications [41]. Cascading refers to using biomass resources consecutively for multiple applications, for example first as a material and later for energy production [98]. Prioritisation according to value is particularly popular with Dutch stakeholders (Chapters 3 and 5), mainly using the 'value pyramid', which ranks different biomass applications and sectors, for example food, chemicals and fuels, in terms of added value [9]. Generally, these concepts aim at using biomass resources efficiently for multiple products and favour higher-value applications. An important problem of these concepts is, however, what efficiency they are actually measuring or striving to improve. Stakeholders usually assume that these concepts address maximisation of sustainability, but often it is either unclear how efficiency is defined, or other criteria are more important. Biorefineries and cascading aim at improved material flows, producing more products from a certain amount of biomass. If this leads to more conventional products being replaced, and thus more fossil resource use being avoided, this may indeed improve the sustainability of biomass use, but this is not self-evident. Case by case analysis of whole value chains would be needed to assess and compare application combinations. But sustainability evaluation tools, such as life-cycle assessment, often do not take multiple uses into account. Multiple products make the evaluation far more complex, as multiple reference markets have to be analysed. Prioritisation using the 'value pyramid' and similar tools does not primarily aim at increased sustainability to begin with, it prioritises based on economic merit of different product groups. As shown in Chapter 6, many energy applications of biomass actually achieve greater GHG reductions than material applications, even though they are ranked lower on the pyramid. Relying on these concepts to choose applications can thus be misleading if it is assumed that a greater contribution to sustainability will be achieved. This thesis showed that sustainability evaluation of biomass applications is important, but often omitted in practice because it is time and cost intensive. Results depend on the factors chosen for comparison. Chapter 5 showed that formal, objective ranking methods to compare biomass uses are lacking. This makes it difficult for stakeholders to make an informed choice, resulting in trial and error approaches and evaluation based on gut feeling. While there is a growing desire of public organisations to steer towards sustainable use of biomass, this lack of ranking criteria leaves room for interpretation and revealed a dilemma between evaluating based on societal value (including sustainability) and evaluating based on costs. In practice, value and costs are (seemingly unconsciously) mixed up and costs are then more influential (Chapter 5).

### 7.3.3 Choice of applications in practice

Next to the evaluation of efficiency in contributing to sustainability, other challenges regarding the choice of applications are related to practical considerations and policies. Even though bioeconomy concepts such as cascading and biorefineries, aiming to achieve multiple applications of biomass, are valued highly by stakeholders, current practice is dominated by a competition for resources between different applications that is usually won by energy applications (Chapter 3). Subsidies developed from a single-policy perspective hinder efficient resource use, and diverging goals of different policy domains concerned with biomass use are a barrier for the development of innovative connections between them.

### 7.3.4 Strategic choice

To achieve a contribution of the bioeconomy to sustainability, it is important to include strategic considerations of which biomass applications are more societally relevant than others. GHG emission reductions are an important factor, but possibilities to solve other societal problems should be included, as well. As discussed in Section 7.1, biomass resources are scarce in comparison with the growing demand and hopes placed on the bioeconomy, so it is crucial to evaluate what biomass should be used for first. This includes three important considerations: First, it should be considered whether an application of biomass is a priority and solving an urgent problem. In Chapter 5 and 6, two applications of residual biomass in current practice are described that arguably do not solve an urgent problem. Direct application of residual biomass on agricultural land to improve soil quality, instead of composting the same biomass and applying the compost, is actually aiming at the same function but is not a proven strategy and probably less effective than the current composting route. And the use of grass in cardboard production replaces a different biomass resource, paper, which is already produced and recycled very efficiently. Second, it should be assessed whether sustainable alternatives to conventional (fossil-based) products can be achieved with other resources than biomass. In many material applications, for example organic chemicals and end products derived from them, biomass is the only possibility to replace fossil resources. This is, in the short to medium term, also true for energy applications in energy intensive sectors, like aviation, shipping and industrial steam production. Other energy products, including electricity and household heating, can be provided by other renewable resources, although the potential scale up may be insufficient to achieve climate mitigation goals. Third, it should be evaluated in which cases biomass can contribute to sustainability by providing characteristics to products that cannot, or only with greater difficulty, be achieved with other resources. Biodegradability is, for example, an attractive characteristic of some bio-based products. In cases where the products end up in the environment, biodegradability can avoid negative consequences. Examples are chainsaw lubricants or surfactants and paints in outdoor use. If products do not end up in the environment but can be collected to enter waste treatment, biodegradability is not advantageous, as it results in loss of resources after only one application. Bio-based products that are designed to be recyclable are then preferable. Evaluation of the contribution to societal problems may result in controversial results. For example, Chapter 6 showed that energy applications can be the most GHG advantageous, but material applications can be preferable if energy is produced with other renewable energy sources.



### 7.3.5 Conclusion: Ranking based on sustainability

Future research should develop methods to define the most efficient use of all biomass resources, including residual biomass. Additionally, policy makers will have to prioritise between different societal functions. The value pyramid is an attempt to do this, but ranking is not actually based on general societal merit but on added economic value. In the future, sustainability should be at the core of ranking methods. Policies should also be developed across different sectors and policy domains, jointly aiming at optimal resource use for multiple goals, rather than inciting competition between applications.

## 7.4 The meanings of sustainability

### 7.4.1 Biomass use for a sustainable future

Biomass can contribute to a sustainable future by providing renewable resources for human consumption. Using renewable resources can help to avoid exhaustion of natural resources, which is one of the most important underlying problems addressed by the concept of sustainability. From the very beginning, the term 'sustainable' was related to biomass use: it first emerged in discourse about the state of German forestry, facing potential shortages of wood [255–257]. Later, the concepts of sustainability and sustainable development expanded to cover globally inclusive development [258]. Nowadays it addresses multiple dimensions, including ecological aspects, such as preserving natural resources and avoiding pollution, but also social and economic dimensions. The bioeconomy relates to all these dimensions (Chapter 2), but this thesis focused on the potential to provide renewable resources. This has two important sides: on the one hand, biomass offers the potential to replace non-renewable fossil resources in the production of products and can therefore contribute to a more sustainable situation. On the other hand, increased demand for sustainable products can also have an adverse effect: biomass might be overused, resulting in the same unsustainable situation that first triggered the use of the term sustainable. Sustainable management of ecosystems, together with sustainable agriculture and forestry, are required to provide biomass. This thesis showed that only if biomass is supplied sustainably and used wisely can the use of biomass contribute to a more sustainable future.

### 7.4.2 Sustainability of the bioeconomy and residual biomass

This thesis examined the sustainability of the bioeconomy and residual biomass from both a theoretical and a practical perspective. In the scientific literature, a majority of papers considers the relationship between bioeconomy and sustainability as generally positive (Chapter 2). However, most publications also acknowledge problems and discuss conditions and possible interventions for these problems. Sustainability is considered as important goal and context of the bioeconomy. From a practical perspective, a trend can be observed from choosing the cheapest way to get rid of residual biomass to exploring societally relevant uses (Chapter 5). Selection of sustainable uses is gaining importance and influences the way vegetation management is organised. New organisational instruments are developed and applied in which sustainable use of residual biomass is promoted. There is a growing desire of public organisations to be able to steer towards sustainable use of residual biomass. However, there is a lack of objective, easily applicable ranking criteria.

### 7.4.3 Analysing sustainability

Analysing the contribution to sustainability of biomass uses is difficult but crucial and applicable methodologies are desired by stakeholders. One of the most important factors of analysis concerns GHG emissions along the value chain of biomass uses. GHG emissions are an important sustainability aspect because human GHG emissions cause climate change, one of the most important sustainability challenges today. Reduction of GHG emissions is also one of the most important drivers of the bioeconomy (Chapter 2). The GHG emissions and savings of residual biomass use were analysed in Chapter 6, comparing various applications of residual biomass, showing that extraction and application of residual biomass can contribute to climate change mitigation. It is, however, crucial to choose GHG beneficial applications: only five out of 13 applications analysed showed clear GHG savings. Chapters 4 and 6 acknowledge that contribution to climate change mitigation is only one of the ecosystem services that residual biomass can fulfil, and that there are other factors than GHG emissions that should be evaluated and taken into consideration, as well. These include both potential contributions of biomass uses and potential impacts that the repurposing or extraction of residual biomass can have. Contributions identified are the replacement of fossil resources, mitigating the disturbance of biogeochemical flows, producing environmentally friendly products and cultural ecosystem services. Impacts of extraction include loss of ecosystem services such as provision of habitats and biodiversity, impacts on soil fertility and quality, carbon and nutrient losses and iLUC. What complicates sustainability analysis even further is that while the basic methodology (life cycle analysis) is well known, it is complicated and controversial and in practice often not applicable because it is time intensive and expensive. As introduced in Chapter 1, one of the most controversial issues is the consideration of iLUC. And even while focussing on GHG emissions as the only impact, there are various factors to consider, such as counterfactuals of current and new applications, multiple uses of biomass and biogenic $CO_2$ (Chapter 6).

### 7.4.4 Conclusion: Sustainability of residual biomass

Using residual biomass instead of cultivated biomass is one of the strategies suggested by the scientific literature to make biomass use more sustainable. This thesis showed that in practice, economic considerations are at least as influential as sustainability. Extraction and application of residual biomass for bioenergy and bio-based products can achieve a GHG benefit and thus contribute to sustainability. But not all applications achieve GHG benefits, and other contributions of bio-based products and impacts of extracting biomass should be considered.

## 7.5 Methodological reflections

This study approached the sustainability of biomass use from different angles, using different methods and integrating practical knowledge of various stakeholders. In this section the methodological choices in the empirical chapters (Chapters 3, 5 and 6) and the value of the different types of data will be reflected upon.

### 7.5.1 Methodological choices

This thesis looked at different aspects of the relationship between sustainability and the bioeconomy and the conditions under which the use of residual biomass contributes to sustainability. To investigate these aspects, different methods were chosen that are best suited to address the diverging goals, presented in Table 1.1. The empirical chapters in this thesis used partly qualitative (Chapters 3 and 5) and partly quantitative (Chapter 6) methods, as these fitted the goals of the chapters best. In order to approach the open-ended, explorative questions of Chapters 3 and 5, semi-structured interviews with purposefully selected stakeholders were conducted. This ensured that participants were interviewed that would help to understand the problem and research question [55]. Both chapters addressed societal stakeholders' knowledge to gather insights on current practice. Chapter 3 focussed on aspects of biomass use that are influenced by policies, gathering information on how two policy domains influence current practice. Chapter 5 analysed drivers and organisational structures influencing residual biomass use. It was found that the qualitative approach and the chosen methodology in Chapters 3 and 5 worked well in both cases. The obtained information provided a good understanding of the opportunities and barriers to improve current practice towards biomass use contributing to sustainability. Chapter 6 addressed a closed-ended question with numeric data, so a quantitative approach was chosen. This provided a clear answer to the question of which current applications of residual biomass result in the lowest net GHG emissions. Furthermore, it provided insights into the different aspects that should be considered when engaging in this type of comparison.

As introduced in Section 1.3., in transdisciplinary settings, scientific knowledge is integrated with input from societal stakeholders [54]. This dissertation project approached the sustainability of biomass use from different angles, integrating practical knowledge of various stakeholders. Practical relevance, established in personal communication with stakeholders, also influenced the choice of the goals and research questions of the empirical chapters. Stakeholders were considered as source of information about current practice, including practical information and experiences. This transdisciplinary approach provided valuable insights both within the different chapters and across the whole thesis. It helped shape the research to be societally relevant, providing results that can help inform policies and practitioners to make informed choices on biomass use.



### 7.5.2 The value of diverse data

The combination of theoretical, qualitative and quantitative data gathered in the different chapters proved of great value to this dissertation project. It helped shape societally relevant research questions, provided input for parameterisation and delivered a mix of results that helped understand the complex choices influencing the contribution of biomass use to sustainability discussed in this chapter. The different types of data influenced the research for this dissertation project across the different chapters. Chapters 2 and 4 provided a broad array of theoretical background information on the bioeconomy and residual biomass, showing for example that the comparison of different applications of biomass is crucial to ensure a contribution to sustainability. Potential applications of biogas were explored in Chapter 3, and applications of residual biomass were compared quantitatively in Chapter 6. Additionally, the background of choosing different applications was investigated in Chapter 5. Chapter 5 showed that there is a need for objective, quantitative comparison of different applications. Chapter 6 provides important building blocks and data for future choices between different applications. Additionally, Chapter 5 provided info on which biomass applications are currently realised and why these are chosen. This helped select applications to compare for Chapter 6 and provided information for parameterisation. Qualitative data incorporating stakeholder knowledge delivered insights in current practice and challenges and on lack of knowledge. Without these insights, the quantitative study in Chapter 6 looking more closely at one of the issues that came up in Chapter 5 might not have been as practically relevant.

## 7.6 Limitations and recommendations for future research

This section provides an overview of issues that remain unanswered in this thesis and gives recommendations for further research.

### 7.6.1 Limitations

The broad scope chosen for this dissertation project resulted in a great variety of relevant topics being discussed in this book. At the same time, many aspects were mentioned but not researched intensively. While Chapter 2 dealt with the sustainability of the bioeconomy from a broad perspective, including environmental, social and economic issues, the remainder of this thesis only considered the environmental dimension of sustainability, focussing on the supply of renewable resources as discussed in Section 7.4.1. Chapter 3 argued that biomass use should be addressed from a broad sustainability perspective including economic and environmental impacts, but only environmental aspects were identified and only GHG emissions were quantified in the subsequent chapters. Additional environmental impacts (listed in Section 7.4.3), but also social and economic impacts of biomass use should be addressed in future research. Additional environmental impacts should be quantified in a more comprehensive analysis of the sustainability of different biomass applications. Finally, the practical applicability of the insights from this study could be improved by discussing the results of this dissertation project with stakeholders and developing methods to compare and rank biomass applications that can be applied by stakeholders. For example, the quantitative results from Chapter 6 could be used to confront choices in practice, for example the prioritisation of material applications over energy described in Chapter 5.

### 7.6.2 Recommendations for future research

To enable adequate analysis of sustainable biomass use, future research should develop methods to define efficient use of biomass resources, including residual biomass. This would help to choose (a set of) applications that contribute to sustainability optimally. Furthermore, methods to assess impacts on sustainability that are difficult to quantify at the moment, such as iLUC or biodiversity, should be developed. Multiple uses of biomass are the focus of concepts such as cascading and the circular economy, but sustainability evaluations often do not take multiple uses into account. The results of comparisons could be improved by including scenarios with consequtive applications. Further quantitative comparison of residual biomass applications should be executed, considering all relevant environmental impacts and including both potential contributions of biomass uses and potential impacts of repurposing or extracting residual biomass. Additionally, social and economic impacts could be identified and considered as well. To ensure wise use of residual biomass resources in the future, potential applications should be compared with current resource uses and with counterfactuals of the products to be replaced. Potentials and applicability of different feedstocks could be compared, considering all second generation biomass feedstocks, including residual biomass and dedicated crops produced on marginal land, but also lignocellulosic and aquatic biomass.



To improve the overall usefulness of biomass use, criteria to prioritise between different biomass uses should be based on both general contributions to sustainability, but also local needs and opportunities for biomass uses, such as depleted soils or a demand for renewable energy provision. But sustainability research has to go beyond prioritising between different biomass applications. It should also consider when it is best not to use any new resources at all, but instead opt for other strategies. The bioeconomy and circular economy approaches should be developed further, considering what biomass could be used for efficiently and what can be solved differently. Behaviour change can contribute to avoiding consumption, for example by reducing packaging materials instead of making them bio-based. New business models may reduce the need for consumption of (bio-based) products, and efficient recycling systems can reduce the need for biomass resources as inputs for production chains. Future research should consolidate concepts such as the bioeconomy and circular economy, and develop decision making tools applying all innovative ideas to ensure resource use that contributes to a sustainable future.

**Herbaceous floodplain vegetation (S. Pfau)**

# Appendix

## Supplementary to Chapter 6

## A1: Description of applications and counterfactuals

Supplementary to Table 6.1.

### A1.1 Biomass left on site and ploughed on site

Woody and grassy biomass are sometimes left at the location where vegetation management takes place (woody biomass left on site, *WLS*, and grassy biomass left on site, *GLS*). This is not allowed in all locations, since biomass may obstruct the water flow. But it does occur, especially when volumes are small. Biomass is usually not stacked up and decomposes naturally under aerobic conditions. These applications do not provide any products and have no counterfactual. Recently, water management organisations entered collaborations with local farmers that plough grassy biomass on fields adjacent to vegetation management sites (grassy biomass ploughed on site, *GPoS*). The aim of GPoS is to increase the organic matter content of the soil, but experience is limited. Fresh biomass generally features lower effective organic matter in comparison to composted biomass, which is frequently used to improve soil organic matter [259]. GPoS may have an effect on soil quality, but this is not reliably quantified and in current practice does not result in a reduced use of fertilisers or other soil improving materials. It is assumed that this application does not have a counterfactual. If GPoS is proven to replace some fertilisers in the future, a counterfactual for this application should be considered. Data on emissions of GPoS are lacking, and it is assumed that emissions are the same as for GLS.

### A1.2 Grazing

Several protected nature areas feature vegetation management by year-round free roaming of large grazing animals; a mix consisting mainly of cattle (70%) and horses (grassy biomass grazing large grazers, *GLG*). Other areas are managed by herds of sheep, spending about nine months in the field and three months in a shed (grassy biomass grazing sheep, *GGS*). In both cases, the main function of the animals is vegetation management, but they also produce small amounts of organic meat replacing conventionally farmed animals as counterfactual.

**A1.3 Energy production**

Bioenergy production from woody biomass includes burning of wood chips in incineration installations to produce either heat (woody biomass heat, *WH*) or heat and electricity in combined heat and power (CHP) plants (woody biomass CHP, *WCHP*). Conventionally produced heat and grid-electricity were assumed as counterfactuals. Grassy biomass can be co-digested together with manure and other co-products to produce biogas. The biogas can then be applied in CHP installations to produce heat and electricity (grassy biomass CHP, *GCHP*), or can be upgraded to green gas (grassy biomass green gas, *GGG*), which can be fed into the gas grid. GCHP counterfactuals are conventionally produced heat and grid-electricity, while natural gas was assumed as counterfactual for GGG. Emissions from green gas and natural gas were compared directly to avoid uncertainties relating to assumptions about applications of gas.

**A1.4 Material production**

Grassy biomass can be turned into compost, which is mainly applied on agricultural fields to improve soil quality (grassy biomass composting for agriculture, *GCA*), replacing artificial fertilisers. It can also be used to replace peat in the production of growth media (grassy biomass composting for growth media, *GCG*). Grassy biomass from vegetation management is sometimes ensilaged and used as livestock fodder (grassy biomass fodder, *GFo*), replacing organic production grass used in organic farming. A relatively new application of grassy biomass is the production of grass fibres (grassy biomass fibres, *GFi*). Grass is treated in a biological process to extract fibres, which are then mixed with pulp from recycled paper to produce cardboard. The grass fibres replace a part of the recycled paper pulp, and the counterfactual is pre-treated waste paper. Pre-treatment of waste paper was assumed to include collection, sorting and re-pulping of the paper [260].

## A2: Formulas GHG emission calculations

Supplementary to Eq. 1-8. All parameters used are presented in Table A1 and Table A2.

### A2.1 Emission vegetation management activities woody biomass ($e_{VM\,(W)}$)

$$\varepsilon_{VM\,(W)} = \mathrm{FQVM}_W \times (\varepsilon_{chainsaw} + \varepsilon_{tractor\ with\ chipper} + \varepsilon_{agricultural\ machine\ with\ chipper})$$

$$\varepsilon_{chainsaw} = \mathrm{HP}_W \times \mathrm{MU}_{CS} \times \mathrm{E}_{PS}$$

$$\varepsilon_{tractor\ with\ chipper} = MU_{TC} \times [HP_W \times W_{TC} \div LTM \times \mathrm{E}_{TP} + FU_{TC} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{TC(\frac{L}{hr})} \div 2 \times DT \div BMH_W \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

$$\varepsilon_{agricultural\ machine\ with\ chipper} = MU_{AM} \times [HP_W \times W_{AM} \div LTM \times \mathrm{E}_{TP} + FU_{AM} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{AM(\frac{L}{hr})} \div 2 \times DT \div BMH_W \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

Data to calculate GHG emissions from vegetation management were based on reports of contractors conducting vegetation management in the Netherlands. Reports were chosen based on relevance from https://www.skao.nl/ketenanalyses. For chainsaw use (including production, fuel use and transport of machinery) a representative ecoinvent record was used. For other machinery, no representative record was available. Instead, we calculated the emission based on the emissions of machinery production, fuel production, fuel consumption and fuel production and consumption for transport of machinery to the maintenance site. Emissions of machinery production were based on Nemecek and Kagi [261]: kg / FU = Weight machine (kg) * operation time (h/FU) /lifetime (h). Fuel consumption during transport is assumed to be 50% of fuel use during full machinery use on vegetation management site, based on Muilwijk and Houben [262].

### A2.2 Emission vegetation management activities grassy biomass ($e_{VM\,(G)}$)

$$\varepsilon_{VM\,(G)} = \mathrm{FQVM}_G \times (\varepsilon_{mowing\ motor\ mower} + \varepsilon_{mowing\ small\ tractor} + \varepsilon_{mowing\ large\ tractor})$$

$$\varepsilon_{mowing\ motor\ mower} = \mathrm{MU}_{MM} \times \mathrm{BMP}_G \times \mathrm{E}_{MM}$$

$$\varepsilon_{mowing\ small\ tractor} = MU_{ST} \times [HP_G \times W_{ST} \div LTM \times \mathrm{E}_{TP} + FU_{ST} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{ST(\frac{L}{hr})} \div 2 \times DT \div BMH_G \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

$$\varepsilon_{mowing\ large\ tractor} = MU_{LT} \times [HP_G \times W_{LT} \div LTM \times \mathrm{E}_{TP} + FU_{LT} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH}) + FU_{LT(\frac{L}{hr})} \div 2 \times DT \div BMH_G \times \frac{1\ kg\ diesel}{1.135\ L\ diesel} \times (\mathrm{E}_{DP} + \mathrm{E}_{DCH})]$$

Data to calculate GHG emissions from vegetation management were based on reports of contractors conducting vegetation management in the Netherlands. Reports were chosen based on relevance from https://www.skao.nl/ketenanalyses. For motor mower use (including production, fuel use and transport of machinery) a representative ecoinvent record was used. For other machinery, no representative record was available. Instead, we calculated the emission based on the emissions of machinery production, fuel production, fuel consumption and fuel production and consumption for transport of machinery to the maintenance site. Emissions of machinery production were based on Nemecek and Kagi [261]: kg / FU = Weight machine (kg) * operation time (h/FU) /lifetime (h). Fuel consumption during transport is assumed to be 50% of fuel use during full machinery use on vegetation management site, based on Muilwijk and Houben [262].

### A2.3 Biogenic $CO_2$ emission woody biomass ($e_{B\,(WLS,\,WH,\,WCHP)}$)

$$\varepsilon_{B\,(WLS,WH,WCHP)} = 1000 \times DM_W \times C_W \times \frac{44}{12} \times E_{CinCO2\,(WLS,WH,WCHP)} \times (fBMP_{WHigh} \times GWPbio_{5yr} + fBMP_{WLow} \times GWPbio_{20yr})$$

### A2.4 Emission of biomass transport to processing location ($e_{T\,(WH,\,WCHP,\,GGG,\,GCHP,\,GCA,\,GCG,\,GFi)}$)

$$\varepsilon_{T\,(WH,WCHP,GGG,GCHP,GCA,GCG,GFi)} = 2 \times TD_{(WH,WCHP,GGG,GCHP,GCA,GCG,GFi)} \times \mathrm{E}_T$$

### A2.5 Emission woody biomass left on site ($e_{WLS}$)

$$\varepsilon_{WLS} = \varepsilon_{VM\,(W)} + \varepsilon_{B\,(WLS)} + \varepsilon_{D\,(WLS)}$$

$$\varepsilon_{D\,(WLS)} = 1000 \times DM_W \times C_W \times fE_{CinCH4} \times \frac{16}{12} \times \mathrm{GWP}_{CH4} + 1000 \times DM_W \times N_W \times fE_{NinN2O} \times \frac{44}{28} \times \mathrm{GWP}_{N2O}$$

### A2.6 Emission woody biomass heat ($e_{WH}$)

$$\varepsilon_{WH} = \varepsilon_{VM\,(W)} + \varepsilon_{T\,(WH)} + \varepsilon_{P\,(WH)} + \varepsilon_{B\,(WH)} - \varepsilon_{C\,(WH)}$$

$$\varepsilon_{P\,(WH)} = CV_{W50\%} \times EF_{H>500kW} \times fI_{5MW} \times \mathrm{E}_{H5MW} + CV_{W50\%} \times EF_{H>500kW} \times fI_{1MW} \times \mathrm{E}_{H1MW} + CV_{W40\%} \times EF_{H<500kW} \times fI_{0.3MW} \times \mathrm{E}_{H0.3MW}$$

$$\varepsilon_{C\,(WH)} = (CV_{W50\%} \times EF_{H>500kW} \times fI_{5MW} + CV_{W50\%} \times EF_{H>500kW} \times fI_{1MW} + CV_{W40\%} \times EF_{H<500kW} \times fI_{0.3MW}) \times \mathrm{E}_{HNG}$$

Processing emissions are the sum of the emissions of heat production in different installation sizes. The emissions retrieved from ecoinvent records include the infrastructure and energy consumption or processing installations.

### A2.7 Emission woody biomass CHP ($e_{WCHP}$)

$$\varepsilon_{WCHP} = \varepsilon_{VM\,(W)} + \varepsilon_{B\,(WCHP)} + \varepsilon_{T\,(WCHP)} + \varepsilon_{P\,(WCHP)} - \varepsilon_{C\,(WCHP)}$$

$$\varepsilon_{P\,(WCHP)} = (EF_{WCHPel} \times f_{WCHPel} + EF_{WCHPth} \times f_{WCHPth}) \times CV_{W50\%} \times \mathrm{E}_{CHPWood}$$

$$\varepsilon_{C\,(WCHP)} = EF_{WCHPel} \times f_{WCHPel} \times CV_{W50\%} \times \mathrm{E}_{El} + EF_{WCHPth} \times f_{WCHPth} \times CV_{W50\%} \times \mathrm{E}_{HNG}$$

The ecoinvent record $E_{CHPWood}$ includes the infrastructure, energy and material consumption of the processing installation.

### A2.8 Emission grassy biomass left on site ($e_{GLS}$)

$$\varepsilon_{GLS} = \varepsilon_{VM\,(G)} + \varepsilon_{D\,(GLS)}$$

$$\varepsilon_{D\,(GLS)} = E_{N2OGLS} \times \mathrm{GWP}_{N2O}$$

We assume that $CH_4$ emissions do not occur due to aerated decay.

### A2.9 Emission grassy biomass ploughed on site ($e_{GPoS}$)

$$\varepsilon_{GPoS} = \varepsilon_{VM\ (G)} + \varepsilon_{P\ (GPoS)} + \varepsilon_{D\ (GPoS)}$$

$$\varepsilon_{P\ (GPoS)} = AP \times \mathrm{E}_{Til}$$

$$\varepsilon_{D\ (GPoS)} = E_{N2OGPoS} \times \mathrm{GWP}_{N2O}$$

Processing emissions are the emissions of the ploughing activities, ecoinvent record $E_{Til}$ includes the construction of machinery and energy consumption.

### A2.10 Emission grassy biomass green gas ($e_{GGG}$)

$$\varepsilon_{GGG} = \varepsilon_{VM\ (G)} + \varepsilon_{T\ (GGG)} + \varepsilon_{P\ (GGG)} - \varepsilon_{C\ (GGG)}$$

$$\varepsilon_{P\ (GGG)} = BGY \times E_{biogas} + BGY \times EF_{BGtoGG} \times \mathrm{E}_{biogastoCH4}$$

$$\varepsilon_{C\ (GGG)} = BGY \times EF_{BGtoGG} \times R_{NGbyGG} \times (E_{NG} + \mathrm{E}_{MC})$$

Combustion of green gas can replace combustion of natural gas in all energy applications, so we compare green gas combusted with natural gas combusted and thus include the difference in biogenic vs. fossil carbon emissions.

### A2.11 Emission grassy biomass biogas CHP ($e_{GCHP}$)

$$\varepsilon_{GCHP} = \varepsilon_{VM\ (G)} + \varepsilon_{T\ (GCHP)} + \varepsilon_{P\ (GCHP)} - \varepsilon_{C\ (GCHP)}$$

$$\varepsilon_{P\ (GCHP)} = BGY \times E_{biogas} + BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times E_{biogasCHP}$$

$$\varepsilon_{C\ (GCHP)} = BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times f_{GCHPth} \times E_{HNG} + BGY \times EY_{BGCHP} \times \mathrm{EF}_{GCHP} \times f_{GCHPel} \times E_{El}$$

Processing emissions include biogas production and biogas conversion to heat and power. Ecoinvent record $E_{biogasCHP}$ includes infrastructure and material consumption.

### A2.12 Emission grassy biomass compost for agriculture ($e_{GCA}$)

$$\varepsilon_{GCA} = \varepsilon_{VM\ (G)} + \varepsilon_{T\ (GCA)} + \varepsilon_{P\ (GCA)} - \varepsilon_{C\ (GCA)}$$

$$\varepsilon_{P\ (GCA)} = \frac{1}{250{,}000} \times E_{CF} + DC_{GC} \times (E_{DP} + E_{DCI}) + \mathrm{ElC}_{GC} \times E_{El} + E_{N2OGC} \times E_{N2O} + E_{CH4GC} \times E_{CH4} + DC_{GCA} \times (E_{DP} + E_{DCI}) + E_{CH4GCA} \times E_{CH4} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}$$

$$\varepsilon_{C\ (GCA)} = FR_{P2O5GCA} \times E_{Pfert} + FR_{K2OGCA} \times E_{Kfert} + FR_{NGCA} \times E_{Nfert} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}$$

Processing emissions are the sum of the emissions of composting installation production, emissions of diesel and electricity consumption of composting installation, emissions from the composting process, diesel consumption during compost application on agricultural grounds, and emissions of compost application on agricultural grounds. According to ecoinvent record $E_{CF}$ 250,000 tonnes of biomass are treated during the lifetime of an installation, so 1/250000 p / $t_{wb}$ are applied. Counterfactual emissions are the emissions of artificial fertiliser production and application of N fertiliser in $N_2O$.

### A2.13 Emission grassy biomass compost for growth media ($e_{GCG}$)

$$\varepsilon_{GCA} = \varepsilon_{VM\ (G)} + \varepsilon_{T\ (GCA)} + \varepsilon_{P\ (GCA)} - \varepsilon_{C\ (GCA)}$$

$$\varepsilon_{P\ (GCA)} = \frac{1}{250{,}000} \times E_{CF} + DC_{GC} \times (E_{DP} + E_{DCI}) + \mathrm{ElC}_{GC} \times E_{El} + E_{N2OGC} \times E_{N2O} + E_{CH4GC} \times E_{CH4} + DC_{GCA} \times (E_{DP} + E_{DCI}) + E_{CH4GCA} \times E_{CH4} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}$$

$$\varepsilon_{C\ (GCA)} = FR_{P2O5GCA} \times E_{Pfert} + FR_{K2OGCA} \times E_{Kfert} + FR_{NGCA} \times E_{Nfert} + FR_{NGCA} \times \frac{44}{28} \times Fert_{N2O} \times E_{N2O}$$

Processing emissions are the sum of the emissions of composting installation production, emissions of diesel and electricity consumption of composting installation and emissions from the composting process. According to ecoinvent record $E_{CF}$ 250,000 tonnes of biomass are treated during the lifetime of an installation, so 1/250000 p / $t_{wb}$ are applied. Counterfactual emissions are the emissions of peat harvesting and carbon emissions during application of peat in growth media.

**A2.14 Emission grassy biomass fibre ($e_{GFi}$)**

$$\varepsilon_{GFi} = \varepsilon_{VM\,(G)} + \varepsilon_{T\,(GFi)} + \varepsilon_{P\,(GFi)} - \varepsilon_{C\,(GFi)}$$

$$\varepsilon_{P\,(GFi)} = FC_{GFi} \times E_{fac} + SGP \times E_{SGP} + TSR_{GFi} \times E_{Tr} + ElC_{GFi} \times E_{El}$$

$$\varepsilon_{C\,(GFi)} = PR_{GFi} \times P_{GFi} \div BM_{GFi} \times E_{RPP}$$

Processing emissions are the sum of the emissions of factory construction, emission of grass silage, emission of transport of sand removed from the grass, and emission of electricity consumption during processing. Counterfactual emissions are emissions of paperpulp production from waste paper. For the future scenario, construction of a biogas installation and a net electricity production, with excess electricity feeding into the net, are calculated.

**A2.15 Emission grassy biomass fodder ($e_{GFo}$)**

$$\varepsilon_{GFo} = \varepsilon_{VM\,(G)} + \varepsilon_{P\,(GFo)} - \varepsilon_{C\,(GFo)}$$

$$\varepsilon_{P\,(GFo)} = FL_{GFo} \times E_{FL} + SGP \times E_{SGP}$$

$$\varepsilon_{C\,(GFo)} = 1 \times E_{GPO} + SGP \times E_{SGP}$$

Silage grass production is included in both our considered process and the counterfactual. Silage grass production is not represented in the ecoinvent record of the counterfactual, however, based on current practice it is realistic to assume silage for both fodder production from grassland and residual grass. Fodder loading is included in $e_{P\,(GFo)}$, and is part of the counterfactual ecoinvent record $E_{GPO}$.

**A2.16 Emission grassy biomass grazing sheep ($e_{GGS}$)**

$$\varepsilon_{GGS} = \varepsilon_{P\,(GGS)} + \varepsilon_{R\,(GGS)} - \varepsilon_{C\,(GGS)}$$

$$\varepsilon_{P\,(GGS)} = Feed_{GGS} \times E_{GPO}$$

$$\varepsilon_{R\,(GGS)} = E_{RGGS} \times AR_{GGS} \div BMP_{G} \times 365\ days \times GWP_{CH4}$$

$$\varepsilon_{C\,(GGS)} = MP_{GGS} \times E_{SS}$$

Processing emissions are the feed required during the period in which sheep are held in a shed. This is assumed to be supplied from the same landscape in which grazing occurs, and thus considered extensive production.

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**A2.17 Emission grassy biomass grazing large grazers ($e_{GLG}$)**

$$\varepsilon_{GLG} = \varepsilon_{RGLG} - \varepsilon_{C\,(GLG)}$$

$$\varepsilon_{R\,(GLG)} = E_{RGLG} \times AR_{GLG} \div BMP_{G} \times 365\ days \times GWP_{CH4}$$

$$\varepsilon_{C\,(GLG)} = MP_{GLG} \times E_{CS}$$

Table A1: Parameters used in GHG emission calculations. All parameters based on literature, personal communication and own calculations are presented, including the abbreviation used in the formulas in A1., units, values (exception: confidential data), references and comments. Emission data shown in this table are based on literature, emission data from ecoinvent are shown in Table A2.

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| **Multiple applications** | | | | |
| Total woody biomass production public areas | $TBMP_{WP}$ | $t_{wb}$ | 48896 | Calculated as described in methods Section 6.2.3 |
| Total woody biomass production all floodplains | $TBMP_{WA}$ | $t_{wb}$ | 92774 | Calculated as described in methods Section 6.2.3 |
| Total grassy biomass production public areas | $TBMP_{GP}$ | $t_{wb}$ | 322057 | Calculated as described in methods Section 6.2.3 |
| Total grassy biomass production all floodplains | $TBMP_{GA}$ | $t_{wb}$ | 582993 | Calculated as described in methods Section 6.2.3 |
| Grassy biomass production per ha | $BMP_G$ | $t_{wb}$ / ha | 30.4 | Amounts of woody and grassy biomass production per hectare were calculated by dividing the woody and grassy biomass produced in each section, as described in methods Section 6.2.3, by the surface areas of the same section for both biomass types. Subsequently, the average for all sections was calculated for both biomass types. |
| Woody biomass production per ha | $BMP_W$ | $t_{wb}$ / ha | 11.64 | Amounts of woody and grassy biomass production per hectare were calculated by dividing the woody and grassy biomass produced in each section, as described in methods Section 6.2.3, by the surface areas of the same section for both biomass types. Subsequently, the average for all sections was calculated for both biomass types. |
| Fraction of trees in high flow zones (5 y rotation time) | $fBMP_{WHigh}$ | *dimensionless* | 0.47 | Calculated as described in methods Section 6.2.3. Rotation time based on personal communication Rijkswaterstaat. |
| Fraction of trees in low flow zones (20 y rotation time) | $fBMP_{WLow}$ | *dimensionless* | 0.53 | Calculated as described in methods Section 6.2.3. Rotation time based on personal communication Rijkswaterstaat. |
| GWPbio 1y rotation time | $GWPbio_{1y}$ | *dimensionless* | 0 | Cherubini et al. [27]; GWPbio TH100 FIRF. Consequently, $e_{bio}$ of grassy biomass is 0 and thus not considered in formulas. |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| GWPbio 5y rotation time | $GWPbio_{5y}$ | *dimensionless* | 0.02 | Cherubini et al. [27]; GWPbio TH100 FIRF |
| GWPbio 20y rotation time | $GWPbio_{20y}$ | *dimensionless* | 0.08 | Cherubini et al. [27]; GWPbio TH100 FIRF |
| Fraction of C emissions in $CO_2$ | $fE_{CinCO2\ (WLS)}$<br>$fE_{CinCO2\ (WH)}$<br>$fE_{CinCO2\ (WCHP)}$ | *dimensionless* | 0.99<br>1<br>1 | WLS: Based on Wihersaari [263]. Assuming all C not emitted as $CH_4$ emitted as $CO_2$ and accordingly calculated as $E_{CinCO2\ (WLS)} = 1\text{-}E_{CinCH4}$. WH and WCHP: $E_{CinCO2\ (WH,WCHP)} = 1$; assuming all C is emitted as $CO_2$ |
| Fraction dry matter woody biomass | $DM_W$ | *dimensionless* | 0.5 | Best estimate based on literature [212,264–266] |
| Fraction dry matter of grassy biomass | $DM_G$ | *dimensionless* | 0.3 | Best estimate based on literature [212,265,267–271] |
| Caloric value residual wood 50% wet | $CV_{W50\%}$ | MJ / $t_{wb}$ | 8030 | Based on Francescato et al. [272]. Caloric value differs between types of wood and with different moisture contents. Differences between types of wood are negligible, but moisture content is very influential. Since no data was available considering both factors, we chose data considering moisture content. To account for potential differences, we included this parameter in the sensitivity analysis. |
| Caloric value residual wood 40% wet (air dried) | $CV_{W40\%}$ | MJ / $t_{wb}$ | 10120 | Based on Francescato et al. [272]. Caloric value differs between types of wood and with different moisture contents. Differences between types of wood are negligible, but moisture content is very influential. Since no data was available considering both factors, we chose data considering moisture content. To account for potential differences, we included this parameter in the sensitivity analysis. |
| C content wood dry | $C_W$ | *dimensionless* | 0.5 | ECN [273] |
| N content wood dry | $N_W$ | *dimensionless* | 0.004 | ECN [273] |
| Woodchips $m^3$ to t | $Wm^3t$ | *dimensionless* | 0.3 | Based on ecoinvent record heat from woodchips and Dones et al. [274] |
| Grass $m^3$ to t | $Gm^3t$ | *dimensionless* | 0.17 | Van Doorn et al. [270] |

*table continues*

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| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Emission diesel combustion in harvesting machinery | $E_{DCH}$ | kg $CO_2$-eq. / kg diesel | 3.09 | Calculated based on EPA [275] Table 2 and Table 5, Agricultural Equipment |
| Emission diesel combustion in industrial installations | $E_{DCI}$ | kg $CO_2$-eq. / kg diesel | 3.3 | Calculated based on EPA [275] Table 1 |
| Energy yield of Dutch natural gas | $CV_{NG}$ | MJ / $m^3$ | 35.08 | Based on online resources [276,277] |
| $N_2O$ emission factor of nitrogen fertiliser | $Fert_{N2O}$ | *dimensionless* | 0.01 | Based on De Klein et al. [278]; Tier 1 methodology |
| Silage grass produced per tonne biomass | SGP | tonne silage grass / $t_{wb}$ | 0.7 | Based on Jungbluth and Chudacoff [279] |
| **Vegetation management woody biomass ($VM_W$) and grassy biomass ($VM_G$)** | | | | |
| Frequency vegetation management grassy biomass | $FQVM_G$ | times / y | 2 | Based on Muilwijk and Houben [262] and personal communication with Rijkswaterstaat and Water boards |
| Frequency vegetation management woody biomass | $FQVM_W$ | times / y | 1 | personal communication with Rijkswaterstaat and Water boards |
| Harvesting pace grassy biomass | $HP_G$ | h / $t_{wb}$ | 0.23 | Based on Muilwijk and Houben [262] and Velghe et al. [280]. We chose the high end of the range as default value, because the sources refer to maintenance of roadside vegetation. The duration of maintenance execution is assumed to be higher in floodplain areas than along roadsides, because the landscape is more versatile and more difficult to access. |
| Harvesting pace woody biomass | $HP_W$ | h / $t_{wb}$ | 0.91 | Based on Cusveller [281] and Weening [282] |
| Fraction of machine use during vegetation management grassy biomass: large tractor | $MU_{LT}$ | *dimensionless* | 0.13 | Calculated based on data of contractors [262,267,271,283–286] |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Fraction of machine use during vegetation management grassy biomass: small tractor | $MU_{ST}$ | *dimensionless* | 0.45 | Calculated based on data of contractors [262,267,271,283–286] |
| Fraction of machine use during vegetation management grassy biomass: motor mower | $MU_{MM}$ | *dimensionless* | 0.41 | Calculated based on data of contractors [262,267,271,283–286] |
| Fraction of machine use during vegetation management woody biomass: chainsaw | $MU_{CS}$ | *dimensionless* | 0.1 | Cusveller [281] |
| Fraction of machine use during vegetation management woody biomass: tractor with mobile chipper | $MU_{TC}$ | *dimensionless* | 0.4 | Cusveller [281] |
| Fraction of machine use during vegetation management woody biomass: agricultural machine with chipper | $MU_{AM}$ | *dimensionless* | 0.5 | Based on Cusveller [281] and Weening [282] |
| Fuel use large tractor | $FU_{LT}$ | L / h | 18 | Calculated based on data of contractors [262,267,271,283–286] |
| | | kg / $t_{wb}$ | 8.98 | |
| Fuel use small tractor | $FU_{ST}$ | L / h | 12.82 | Calculated based on data of contractors [262,267,271,283–286] |
| | | kg / $t_{wb}$ | 6.4 | |
| Fuel use agricultural machine with chipper | $FU_{AM}$ | L / h | 2.3 | Weening [282] |
| | | kg / $t_{wb}$ | 1.84 | |

*table continues*

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| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Fuel use tractor with mobile chipper | $FU_{TC}$ | L / h | 10 | Cusveller [281] |
| | | kg / $t_{wb}$ | 8.01 | |
| Weight large tractor | $W_{LT}$ | kg | 4000 | Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search |
| Weight large mower | $W_{LM}$ | kg | 3000 | Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search |
| Weight tractor with mobile chipper | $W_{TC}$ | kg | 3000 | Based on ecoinvent record tractor production, 4-wheel, agricultural and internet search |
| Weight agricultural machine with chipper | $W_{AM}$ | kg | 7000 | Based on Weening [282] and internet search |
| Lifetime machinery | LTM | h | 7000 | Based on ecoinvent record tractor production, 4-wheel, agricultural |
| Driving time to and from vegetation management location | DT | h | 1 | Based on Muilwijk and Houben [262], estimating the total driving time to and from location |
| Amount of grassy biomass harvested per assignment | $BMH_G$ | $t_{wb}$ | 2439.65 | Based on Droog [284] and van Doorn [283] |
| Amount of woody biomass harvested per assignment | $BMH_W$ | $t_{wb}$ | 647.05 | Proportional to amount of grassy biomass harvested per assignment, assuming that maintenance is executed in a certain area, maintaining all vegetation in one assignment. Calculated based on the proportion between total biomass production woody and grassy. |
| **Woody biomass left on site (WLS)** | | | | |
| Fraction of C emissions in $CH_4$ | $fE_{CinCH4}$ | *dimensionless* | 0.01 | Based on Wihersaari [263]. We choose the lowest value of the range, because the assumption in this study is wet wood that is piled up, which would result in higher emissions than wood that is spread out, which is the more realistic scenario in our case study. We use the geometric average of the range for piled wood as approximation for the maximum emissions of non-piled wood in the sensitivity analysis. |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Fraction of N emissions in $N_2O$ | $fE_{NinN2O}$ | *dimensionless* | 0.01 | Based on Wihersaari [263]. We choose the lowest value of the range, because the assumption in this study is wet wood that is piled up, which would result in higher emissions than wood that is spread out, which is the more realistic scenario in our case study. We use the geometric average of the range for piled wood as approximation for the maximum emissions of non-piled wood in the sensitivity analysis. |
| **Woody biomass heat (WH)** | | | | |
| Transport distance | $TD_{WH}$ | km | 26.29 | Calculated as described in methods section. |
| Efficiency heat production of installations >500kW | $EF_{H>500kW}$ | *dimensionless* | 0.9 | ECN [287] |
| Efficiency heat production of installations <500kW | $EF_{H<500kW}$ | *dimensionless* | 0.89 | RVO [288] |
| Fraction of installations ~5MWth | $fI_{5MW}$ | *dimensionless* | 0.82 | Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO [242]. Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, $E_{H1MW}$, $E_{H5MW}$ |
| Fraction of installations ~1MWth | $fI_{1MW}$ | *dimensionless* | 0.16 | Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO [242]. Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, $E_{H1MW}$, $E_{H5MW}$ |
| Fraction of installations ~0.3MWth | $fI_{0.3MW}$ | *dimensionless* | 0.02 | Calculated based on the thermic power output of the installations in all identified processing locations, as provided by RVO [242]. Distinction in installations was chosen based on the nominal capacity described in ecoinvent records $E_{H0.3MW}$, $E_{H1MW}$, $E_{H5MW}$ |
| **Woody biomass CHP (WCHP)** | | | | |
| Transport distance | $TD_{WCHP}$ | km | 73.19 | Calculated as described in methods section. |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Efficiency of CHP unit electric | $EF_{WCHPel}$ | *dimensionless* | 0.16 | ECN [287]. For the sensitivity analysis, a higher electric conversion efficiency was assumed. Based on IEA [289], stating an efficiency of 32% and an assumed efficiency loss of 2 percent point, due to drying (based on calorific value of wood and heat of evaporation of water) an efficiency of 30% can be assumed. |
| Efficiency of CHP unit thermic | $EF_{WCHPth}$ | *dimensionless* | 0.8 | ECN [287] |
| Fraction of CHP in electricity | $f_{WCHPel}$ | *dimensionless* | 0.34 | calculated based on ecoinvent record Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 |
| Fraction of CHP in heat | $f_{WCHPth}$ | *dimensionless* | 0.66 | calculated based on ecoinvent record Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 |
| **Grassy biomass left on site (GLS)** | | | | |
| $N_2O$ emissions during natural decomposition | $E_{N2OGLS}$ | kg $N_2O$ / $t_{wb}$ | 0.07 | Calculated based on Velghe et al. [280]. |
| **Grassy biomass ploughed on site (GPoS)** | | | | |
| $N_2O$ emissions during natural decomposition in soil | $E_{N2OGPoS}$ | kg$N_2O$ / $t_{wb}$ | 0.07 | Velghe et al. [280]. Assuming that emissions are similar to left on site on the long term. Little is known about the effect of ploughing on emissions in N2O. N2O is formed in different conditions, which makes reasonable estimates difficult. This parameter is therefore included in the sensitivity analysis. |
| Area ploughed to apply biomass | AP | ha / $t_{wb}$ | 0.2 | Calculated based on Biomassa Alliantie [290] |
| **Grassy biomass green gas (GGG) and biogas CHP (GCHP)** | | | | |
| Transport distance | $TD_{GGG}$ | km | 40.19 | Calculated as described in methods section. |
| Transport distance | $TD_{GCHP}$ | km | 59.05 | Calculated as described in methods section. |
| Biogas yield per tonne grass | BGY | $m^3$ / $t_{wb}$ | 70.23 | Based on Jungbluth and Chudacoff [279] and IVAM [265] |
| Efficiency of biogas to green gas conversion | $EF_{BGtoGG}$ | *dimensionless* | 0.67 | Based on ecoinvent record biogas purification to methane 96 vol-% |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Replacement of natural gas by green gas | $R_{NGbyGG}$ | *dimensionless* | 0.96 | Based on ecoinvent record biogas purification to methane 96 vol-%. Describing a green gas methane content of 96% and $CO_2$ content of 4%, which does not replace natural gas |
| Energy yield from biogas CHP | $EY_{BGCHP}$ | MJ / $m^3$ biogas | 22.69 | Based on IVAM [265] and Biogas-E [276] |
| Fraction of CHP in heat | $f_{GCHPth}$ | *dimensionless* | 0.59 | calculated based on ecoinvent record heat and power co-generation, biogas, gas engine |
| Fraction of CHP in electricity | $f_{GCHPel}$ | *dimensionless* | 0.41 | calculated based on ecoinvent record heat and power co-generation, biogas, gas engine |
| Efficiency CHP unit | $EF_{GCHP}$ | *dimensionless* | 0.9 | calculated based on ecoinvent record heat and power co-generation, biogas, gas engine |
| Density natural gas | DNG | kg / $m^3$ | 0.66 | Based on Air Liquide [291], assuming 1atm pressure and T of 25C |
| $CO_2$ production during methane combustion | $E_{MC}$ | kg $CO_2$ / $m^3$ natural gas | 1.80 | Calculated as $E_{MC}$ = DNG*44,01/16,04. Assuming stoichiometry of methane combustion for small ethane and propane content of natural gas ( ±1% each). |
| **Grassy biomass compost for agriculture (GCA) and compost for growth media (GCG)** | | | | |
| Transport distance | $TD_{GCA}$ | km | 36.62 | Calculated as described in methods section. |
| Transport distance | $TD_{GCG}$ | km | 26.97 | Calculated as described in methods section. |
| Electricity consumption composting process | $EIC_{GC}$ | MJ / $t_{wb}$ | 39.59 | Based on Boldrin et al. [292] and IVAM [265] |
| Diesel consumption composting process | $DC_{GC}$ | kg diesel / $t_{wb}$ | 1.81 | Based on Boldrin et al. [292] and IVAM [265] |
| $N_2O$ Emission composting process | $E_{N2OGC}$ | kg $N_2O$ / $t_{wb}$ | 0.06 | Based on Boldrin et al. [292], IVAM [265] and Velghe et al. [280] |
| $CH_4$ Emission composting process | $E_{CH4GC}$ | kg $CH_4$ / $t_{wb}$ | 0.82 | Based on Boldrin et al. [292], IPCC (2006), IVAM [265] and Velghe et al. [280] |
| Efficiency composting process | $EF_{GC}$ | tonne compost / $t_{wb}$ | 0.56 | Based on Boldrin et al. [292] and IVAM [265] |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Inorganic fertiliser replacement by compost for agriculture: N | $FR_{NGCA}$ | kg N / $t_{wb}$ | 0.89 | Based on Boldrin et al. [292], Velghe et al. [280] and BGK [294] |
| Inorganic fertiliser replacement by compost for agriculture: $P_2O_5$ | $FR_{P2O5GCA}$ | kg $P_2O_5$ / $t_{wb}$ | 1.29 | Based on Boldrin et al. [292], Velghe et al. [280] and BGK [294] |
| Inorganic fertiliser replacement by compost for agriculture: $K_2O$ | $FR_{K2OGCA}$ | kg $K_2O$ / $t_{wb}$ | 4.42 | Based on Boldrin et al. [292], Velghe et al. [280] and BGK [294] |
| Diesel consumption application of compost on agricultural land | $DC_{GCA}$ | kg diesel / $t_{wb}$ | 0.31 | Based on Boldrin et al. [292] |
| Emissions of compost application on agricultural land: $CH_4$ | $E_{CH4GCA}$ | kg $CH_4$ / $t_{wb}$ | 0.0004 | Based on IVAM [265] |
| Emissions of peat application in growth media | $E_{GCPA}$ | kg $CO_2$-eq. / t_peat | 811.39 | Based on Boldrin et al. [292] |
| Efficiency of peat replacement of compost application in growth media | $EF_{GCG}$ | tonne peat / tonne compost | 0.67 | Based on Boldrin et al. [292] and personal communication composting companies Attero and Bruins & Kwast, 2017 |
| Efficiency of peat replacement | $PR_{GCG}$ | tonne peat / $t_{wb}$ | 0.374 | Calculated as $PR_{GCG} = EF_{GC} * EF_{GCG}$ |
| **Grassy biomass fibre (GFi)** | | | | |
| Transport distance | $TD_{GF}$ | km | 74.71 | Calculated as described in methods section. |
| Amount of paper replaced by grass fibers | $PR_{GFi}$ | *dimensionless* | *confidential* | Personal communication NewFoss 2017-2018 |
| Wet biomass input total | $BM_{GFi}$ | $t_{wb}$ / y | *confidential* | Based on silage grass input (Personal communication NewFoss 2017-2018) and SGP |
| NewFoss Fibre end product | $P_{GFi}$ | t / y | *confidential* | Personal communication NewFoss 2017-2018 |
| Sand removal from grass | $SR_{GFi}$ | t / $t_{wb}$ | *confidential* | Personal communication NewFoss 2017-2018 |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Transport distance sand disposal | $TDSR_{GFi}$ | km | *confidential* | Personal communication NewFoss 2017-2018 |
| Transport for and disposal | $TSR_{GFi}$ | $tkm / t_{wb}$ | *confidential* | Calculated as $TSR_{GFi} = TDSR_{GFi} * SR_{GFi}$ |
| Plant operation time | $POT_{GFi}$ | h / y | *confidential* | Personal communication NewFoss 2017-2018 |
| Factory construction required per processed biomass | $FC_{GFi}$ | $m^2 / t_{wb}$ | *confidential* | Personal communication NewFoss 2017-2018. Based on annual processing of biomass and lifetime of 50 years, stated in ecoinvent record Building, hall, steel construction |
| Electricity consumption | $ElC_{GFi}$ | $MJ / t_{wb}$ | *confidential* | Personal communication NewFoss 2017-2018 |
| Emission recycled paper production | $E_{RP}$ | kg $CO_2$-eq. / t_paper | 743.86 | Based on Hillman et al. [295] and Laurijssen et al. [296] and ecoinvent record Paper production, newsprint, recycled |
| Emission of energy use paper recycling | $E_{RPEU}$ | kg $CO_2$-eq. / t_paper | 532.64 | Calculated from Laurijssen et al. [296] and Wang et al. (2012) |
| Emission factor paperpulp, pre-processed from waste paper, before upcycling into new paper | $E_{RPP}$ | kg $CO_2$-eq. / tonne paperpulp | 211.23 | Calculated as $E_{RPP} = E_{RP} - E_{RPEU}$. Merrild et al. [298] established that during the recycling of paper, the upcycling of sorted paper into recycled paper has the highest impact, while upstream processing contributes only marginally to GHG emissions. Energy use for upcycling is identified as one of the most important factors for emissions during paper recycling [260,298,299]. |
| **Grassy biomass livestock fodder (GFo)** | | | | |
| Fodder loading | $FL_{GFo}$ | $m^3 / t_{wb}$ | 56 | Based on ecoinvent record Grass production, permanent grassland, extensive, organic. Included in both our considered process and the counterfactual. |
| **Grassy biomass grazing sheep (GGS) and grazing large grazers (GLG)** | | | | |
| Ruminant $CH_4$ emissions sheep | $E_{RGGS}$ | kg $CH_4$ / head /d | 0.02 | Based on Crutzen et al. [300], Judd et al. [301], Lassey [302], Lassey et al. [303] and Yusuf et al. [304]. |

*table continues*

| Parameter | Abbreviation | Unit | Default value | References and comments |
|---|---|---|---|---|
| Animals required to maintain 1ha for a year | $AR_{GGS}$ | head / ha | 5.24 | Based on data from a pilot along the Twentekanalen in the Netherlands (including data on grazing rounds per year, number of animals in the herd and grazing speed) presented in Boon [305]. Additionally, we made an estimation of sheep required for year-round management, based on a comparison between food uptake of large grazers (cattle and horses) and sheep. We think that this gives a better picture, since the number of animals required with large grazers is based on real-life experience with year-round grazing, while the numbers for grazing with sheep are only based on a short-term pilot. We then aggregated our estimate with the result of the pilot. |
| Feed for grazers during period in shed | $Feed_{GGS}$ | tonne hay / $t_{wb}$ | 0.11 | Calculated from feed requirement in kgDM (Personal communication shepherder involved in the pilot along the Twentekanalen in the Netherlands) as $Feed_{GGS} = kgDM*DM_G/1000*AR_{GGS}/BMP_G$ |
| Meat production mutton and lamb | $MP_{GGS}$ | kg / $t_{wb}$ | 2.1 | Calculated from meat production in kg/hd/y (Personal communication shepherder involved in the pilot along the Twentekanalen in the Netherlands) as $MP_{GGS} = kg/hd/y*AR_{GGS}/BMP_G$ |
| Ruminant $CH_4$ emissions large grazers | $E_{RGLG}$ | kg $CH_4$ / head / d | 0.15 | Based on ruminant emission of cattle of 0.19 $kgCH_4/hd/d$ [300,302–304] and horses of 0.05 $kgCH_4/hd/d$ [300,304] and the fraction of animals that are cattle of 0.7 [306] |
| Animals required to maintain 1ha for a year | $AR_{GLG}$ | head / ha | 1.41 | Based on personal communication with Staatsbosbeheer, 2017, and FREE Nature, 2017 |
| Meat production beef | $MP_{GLG}$ | kg / $t_{wb}$ | *confidential* | Calculated from meat production in kg/hd/y (Personal communication FREE Nature, 2018, confidential) as $MP_{GLG} = kg/hd/y*AR_{GLG}/BMP_G$ |

Table A2: Ecoinvent records used for GHG emission calculations (Wernet et al. [236]). Wherever different geographical representations were available we chose according to the following order of preference: NL, RER, Europe without Switzerland, CH, GLO, RoW.

| Name ecoinvent record | Abbreviation | Geographical representation | Unit | Value | Comments |
|---|---|---|---|---|---|
| **Multiple applications** | | | | | |
| Transport, freight, lorry 16-32 metric ton, EURO5 | $E_T$ | RER | kg $CO_2$-eq. / tkm | 0.17 | Choice based on [262,281,282,307] |
| Tractor production, 4-wheel, agricultural | $E_{TP}$ | CH | kg $CO_2$-eq. / kg machine | 5.73 | |
| Diesel, low-sulfur, market group for | $E_{DP}$ | RER | kg $CO_2$-eq. / kg diesel | 0.6 | |
| Mowing, by motor mower | $E_{MM}$ | CH | kg $CO_2$-eq. / ha | 17.8 | |
| Power sawing, without catalytic converter | $E_{PS}$ | RER | kg $CO_2$-eq. / h | 7.22 | |
| Market for electricity, high voltage | $E_{EI}$ | NL | kg $CO_2$-eq. / MJ | 0.15 | |
| Market for heat, district or industrial, natural gas | $E_{HNG}$ | Europe without Switzerland | kg $CO_2$-eq. / MJ | 0.03 | |
| Grass silage, organic, production | $E_{SGP}$ | CH | kg $CO_2$-eq. / tonne silage grass | 0.1 | |
| Emissions to air; dinitrogen monoxide | $GWP_{N2O}$ | General | kg $CO_2$-eq. / kg | 265 | |
| Emissions to air; methane | $GWP_{CH4}$ | General | kg $CO_2$-eq. / kg | 30.5 | |
| Tillage, ploughing | $E_{Til}$ | CH | kg $CO_2$-eq. / ha | 120 | |
| Grass production, permanent grassland, extensive, organic | $E_{GPO}$ | CH | kg $CO_2$-eq. / tonne | 54.8 | |
| **Woody biomass heat (WH)** | | | | | |
| Heat production, softwood chips from forest, at furnace 300kW | $E_{H0.3MW}$ | CH | kg $CO_2$-eq. / MJ | 0.002 | Input of wood chips excluded for calculation of emission |
| Heat production, softwood chips from forest, at furnace 1000kW | $E_{H1MW}$ | CH | kg $CO_2$-eq. / MJ | 0.002 | Input of wood chips excluded for calculation of emission |

*table continues*

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| Name ecoinvent record | Abbreviation | Geographical representation | Unit | Value | Comments |
|---|---|---|---|---|---|
| Heat production, softwood chips from forest, at furnace 5000kW, state of the art | $E_{H5MW}$ | RoW | kg $CO_2$-eq. / MJ | 0.0054 | Input of wood chips excluded for calculation of emission |
| **Woody biomass CHP (WCHP)** | | | | | |
| Heat and power co-generation, wood chips, 6667kW state of the art 2014 | $E_{CHPwood}$ | RoW | kg $CO_2$-eq. / MJ | 0.00078 | Input of wood chips excluded for calculation of emission |
| Electricity production hard coal, high voltage | $E_{EP}$ | NL | kg $CO_2$-eq. / MJ | 0.29 | Used for alternative scenario sensitivity analysis |
| **Grassy biomass green gas (GGG) and biogas CHP (GCHP)** | | | | | |
| Heat and power co-generation, biogas, gas engine | $E_{biogasCHP}$ | NL | kg $CO_2$-eq. / MJ | 0.00078 | Input of biogas excluded for calculation of emission |
| Market for natural gas, high pressure | $E_{NG}$ | NL | kg $CO_2$-eq. / $m^3$ | 0.14 | |
| Biogas production from grass | $E_{biogas}$ | CH | kg $CO_2$-eq. / $m^3$ | 0.36 | Input of grass excluded for calculation of emission |
| Biogas purification to methane 96 vol-% | $E_{biogastoCH4}$ | CH | kg $CO_2$-eq. / $m^3$ | 0.73 | Input of biogas excluded for calculation of emission |
| **Grassy biomass compost for agriculture (GCA) and compost for growth media (GCG)** | | | | | |
| Nitrogen fertiliser, as N, market for | $E_{Nfert}$ | GLO | kg $CO_2$-eq. / kg | 11.4 | |
| Phosphate fertiliser, as P2O5, market for | $E_{Pfert}$ | GLO | kg $CO_2$-eq. / kg | 2.16 | |
| Potassium fertiliser, as K2O, market for | $E_{Kfert}$ | GLO | kg $CO_2$-eq. / kg | 2.01 | |
| Composting facility, open, construction | $E_{CF}$ | CH | kg $CO_2$-eq. / p | 765,000 | Record describes that 250,000 tonnes of biomass are treated during the lifetime of an installation |
| Peat, production | $E_{PeatP}$ | RoW | kg $CO_2$-eq. / tonne | 10.8 | |
| **Grassy biomass fibre (GFi)** | | | | | |
| Building, hall, steel construction | $E_{Fac}$ | CH | kg $CO_2$-eq. / $m^2$ | 399 | Record assumes a factory life time of 50 years |

*table continues*

| Name ecoinvent record | Abbreviation | Geographical representation | Unit | Value | Comments |
|---|---|---|---|---|---|
| Anaerobic digestion plant construction, for biowaste | $E_{ADP}$ | CH | kg $CO_2$-eq. / p | 1,020,000 | Record assumes a installation lifetime of 25 years. Used for alternative scenario. |
| Paper production, newsprint, recycled | $E_{PaperP}$ | CH | kg $CO_2$-eq. / tonne | 735 | |
| **Grassy biomass livestock fodder (GFo)** | | | | | |
| Fodder loading, by self-loading trailer | $E_{FL}$ | CH | kg $CO_2$-eq. / $m^3$ | 0.69 | |
| **Grassy biomass grazing sheep (GGS) and grazing large grazers (GLG)** | | | | | |
| Sheep for slaughtering | $E_{SS}$ | RoW | kg $CO_2$-eq. / kg | 13 | |
| Cattle for slaughtering | $E_{CS}$ | RoW | kg $CO_2$-eq. / kg | 14.2 | |

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Table A3: Identification of processing locations

| Application | Number of processing locations identified | References |
|---|---|---|
| Woody biomass heat | 28 | Bio-energy cluster Oost-Nederland [308]; RVO [242]; personal communication Staatsbosbeheer |
| Woody biomass CHP | 3 | Bio-energy cluster Oost-Nederland [308]; RVO [242]; personal communication Staatsbosbeheer |
| Grassy biomass green gas | 4 | Brinkmann [271]; personal communication Bio-energie cluster Oost-Nederland, Bruins & Kwast and Staatsbosbeheer; online search. Specific selection of installations capable of co-digesting grass |
| Grassy biomass biogas CHP | 8 | Brinkmann [271]; personal communication Bio-energie cluster Oost-Nederland, Bruins & Kwast, Staatsbosbeheer; online search. Specific selection of installations capable of co-digesting grass |
| Grassy biomass fibre | 1 | NewFoss [309] |
| Grassy biomass compost for agriculture | 13 | BVOR [310] |
| Grassy biomass compost for growth media | 38 | BVOR [310] |

Flooding of Rhine floodplain, Nijmegen, The Netherlands (S. Pfau)

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Biomass released during floodplain management (H. de Coninck)

# Summaries

English summary

Nederlandse samenvatting

Deutsche Zusammenfassung

## SUMMARY

The extensive use of fossil resources for the production of energy and materials has many negative consequences, including human-induced climate change, air pollution and land degradation. One approach to reduce our dependence on fossil resources is to use biomass as organic raw material, switching from a fossil economy to a bioeconomy. The bioeconomy promises a way out of fossil resource consumption, while continuing the provision of commodities in a more sustainable way. But many scientific controversies and societal debates cast doubts on the validity of this promise, and in recent years it has become apparent that the bioeconomy is not a miracle cure.

Many choices influence whether biomass use contributes to a sustainable future, as discussed in **Chapter 1**. For example, the claim that bioenergy is carbon neutral is often debated, revolving around the origin and production of biomass. Cultivating biomass specifically for energy and material applications results in the occupation of land and can cause direct and indirect land-use change.

The drawbacks of cultivating biomass have shifted the focus to residual biomass, which is not produced specifically for the market but is a by-product of other activities. One of these activities is vegetation management in riverine landscapes. High and dense vegetation lowers the water conveyance capacity of river floodplains and increases flood risk. In densely populated riverine landscapes, such as the Rhine delta in the Netherlands, floodplain vegetation is managed regularly to minimise risk of flooding in inhabited areas. The resulting residual biomass is increasingly considered a valuable resource for the bioeconomy.

However, residual biomass is seldom without function and if resources are redirected to new applications, the original function can be lost. The contribution of residual biomass use to sustainability has to be assessed carefully.

Against the background of the pros, cons and limitations of the bioeconomy, this thesis had two main objectives: first, to explore the relationship between sustainability and bioeconomy, and second, to investigate the conditions under which the use of residual biomass contributes to sustainability. For the latter, residual biomass released during

landscape management in riverine areas was used as a case study. Overarchingly, this thesis describes and discusses different choices that influence whether biomass use contributes to a sustainable future.

**Chapter 2** describes the results of a systematic review of scientific literature regarding the views expressed about the sustainability of the bioeconomy. There is considerable attention for sustainability in the scientific bioeconomy debate, but the views on this topic range from positive to negative. This chapter discusses various trends as well as conditions for a contribution to sustainability, including sustainable biomass production and the efficient use of resources. It is concluded that the bioeconomy is not self-evidently sustainable; various risks and pitfalls have to be considered and avoided.

One of the prevailing applications of both cultivated and residual biomass is the production of biogas. Biogas plays an important role in bioeconomy policies, but also in the renewable energy policy domain, resulting in a competition over scarce biomass resources between policy domains. **Chapter 3** analyses how biogas can contribute to both policy domains. Based on interviews with stakeholders, this chapter provides an in-depth assessment of the current practice of biogas production. It is argued that biomass use for biogas production can contribute to both renewable energy and bioeconomy goals, but efficient resource use is currently hindered by conflicting policy goals and instruments.

In **Chapter 4**, the results of a literature study on the sustainability of residual biomass are presented. It features the history of biomass supply and demand and the consequences for sustainability. Furthermore, this chapter discusses advantages and disadvantages of residual biomass, focusing on possible consequences from changing resource use. Advantages include forgoing land-use change, reducing waste and increasing the overall efficiency of resource use. Challenges of residual biomass use include a lower quality due to high heterogeneity, negative impacts related to changing the use of the resource and spatial availability, as they are usually by-products of other processes. This chapter shows that residual biomass use can contribute to sustainability under certain conditions, but is not a silver bullet. The benefits of using it for new applications should outweigh the loss of former uses.

Residual biomass requires different considerations than cultivated biomass: while with cultivated biomass the land use might change, with residual biomass it is the resource use and the functions that residues might have that change, with a different set of consequences. Various factors should be considered, including the potential to reduce GHG emissions, replace fossil resources, mitigate disturbance of biogeochemical flows and produce environmentally friendly products.

Residual biomass from vegetation management in riverine areas is increasingly considered by Dutch water management organisations as a valuable ecosystem service instead of a waste product. **Chapter 5** explores this transition. This chapter is based on a broad analysis of vegetation management practices and subsequent biomass use, supplemented by interviews with employees of water management organisations responsible for vegetation management. The results show a trend for water management organisations to consider sustainability in their choice of biomass applications. In the decision-making process, new organisational instruments are developed and applied in which sustainable use of residual biomass is promoted. However, there is a lack of objective, easily applicable ranking criteria. This makes it difficult for stakeholders to make an informed choice, resulting in trial and error approaches and evaluation based on gut feeling. This also revealed a dilemma between evaluating based on societal value (including sustainability) and evaluating based on costs. In practice, value and costs are (seemingly unconsciously) mixed up and costs are then more influential.

One of the factors considered most important when comparing biomass applications is the net greenhouse gas emission. **Chapter 6** presents the results of a quantitative study comparing the life cycle greenhouse gas benefits or burdens of residual biomass applications. The study considered thirteen current applications. The calculations included counterfactuals, such as the emissions saved by applications through the replacement of a benchmark product. This chapter shows that greenhouse gas emissions differ substantially and can achieve significant benefits or burdens, depending on choice of applications. It is concluded that the greenhouse gas emissions of these different applications should be compared and considered in decision making. It is crucial to consider counterfactuals of each application, including the products that are replaced, but also current uses of residual biomass. The chapter shows that the considered bioenergy applications were generally more greenhouse gas beneficial than the currently available material applications. Strikingly, this is in contrast with the feeling that many practitioners described in the interviews conducted for **Chapter 5**, who often considered material applications to be preferable.

**Chapter 7** discusses the results and conclusions of all chapters in light of the choices that influence whether (residual) biomass use contributes to a sustainable future. Choosing biomass instead of fossil resources is a promising way to make a 'green choice', reducing negative consequences of our consumption behaviour. However, results from this thesis show that choosing biomass does not necessarily contribute to sustainability. The bioeconomy can play an important role only if sustainability is a central goal and consideration.

Choosing residual biomass as raw material can be a sustainable alternative to cultivated biomass. However, this thesis showed that residual biomass is usually not without function and the impact of choosing a different application should be closely evaluated and considered. Residual biomass is furthermore a challenging resource, for example, regarding spatial availability and quality. Residual biomass is a by-product of other processes and its provision cannot be scaled up easily. It is therefore not practical to consider potential applications of residual biomass without resource availability in mind. Where residual biomass is available and can potentially provide greater societal value than traditional uses or functions, it is useful to compare new applications.

This thesis showed that in practice the value of residual biomass is a very influential factor in its use over cultivated biomass. Producers of energy and materials are increasingly interested in less attractive, less readily available and difficult to process biomass, including many residual biomass sources. However, this is not due to the fact that residual biomass is considered more sustainable, but that it is usually cheaper. Biomass owners expect the value of residual biomass to increase in the future, but based on the results of this study it can be concluded that residual biomass will probably not increase much in value in the near future. Bio-based products compete with cheaper fossil products, so producers cannot afford to pay more for biomass, especially when it requires more processing.

The results of this thesis, especially **Chapter 6**, show that biomass applications have different impacts. Making a 'green choice' should include choosing applications based on their contribution to sustainability. In the evaluation of different uses, sustainability should be at the core. It is recommended that methods to define the most efficient use of all biomass resources are developed. This thesis showed that sustainability evaluation of biomass applications is important, but often omitted in practice because it is time and cost intensive.

Policy makers are advised to prioritise between societal functions of different applications. This includes three important considerations: First, it should be considered whether an application of biomass solves an urgent problem. Second, it should be assessed whether sustainable alternatives to conventional (fossil-based) products can be achieved with resources other than biomass. Third, it should be evaluated in which cases biomass can contribute to sustainability by providing characteristics to products that cannot, or only with greater difficulty, be achieved with other resources. Policies should be developed across different sectors and policy domains, jointly aiming at optimal resource use for multiple goals, rather than inciting competition between applications. Furthermore, more consideration should go into the consolidation of the bioeconomy and circular economy concepts, determining which strategy is best to achieve increased sustainability in which situation.

The bioeconomy relates to the ecological, social and economic dimensions of sustainability. This thesis mainly focussed on the potential provision of renewable resources and the benefits that bio-based energy and materials can have in comparison to fossil-based products. This has two important aspects: on the one hand, biomass offers the potential to replace non-renewable fossil resources in the production of products and can contribute to a more sustainable situation. On the other hand, increased demand for sustainable products can also have an adverse effect: biomass might be overused, resulting in the same unsustainable situation that first triggered the use of the term sustainable. Sustainable management of ecosystems, together with sustainable agriculture and forestry, are required to provide biomass. This thesis showed that only if biomass is supplied sustainably and used wisely can its use contribute to a more sustainable future.

## SAMENVATTING

Het grootschalige gebruik van fossiele brandstoffen voor de productie van energie en materialen zoals plastic heeft negatieve gevolgen, waaronder klimaatverandering, lucht vervuiling en de verwoesting van landschappen. Eén strategie om onze afhankelijkheid van fossiele grondstoffen te reduceren is het gebruik van biomassa als organische grondstof, waarbij om wordt geschakeld van een fossiele economie naar een bio-based economie. De bio-based economie beloofd een uitweg uit de uitputting van fossiele grondstoffen, waarbij consumptiegoederen op een duurzame manier vervaardigd worden. Diverse wetenschappelijke controverses en maatschappelijke debatten geven echter aan dat er twijfels bestaan over hoe reëel deze belofte is.

In de afgelopen jaren is gebleken dat de bio-based economie geen panacee is. Of, en in welke mate, het gebruik van biomassa bijdraagt aan een duurzame toekomst, wordt beïnvloed door vele variabelen en keuzes, zoals besproken in **Hoofdstuk 1**. De veronderstelling dat bio-energie koolstof neutraal is wordt bijvoorbeeld vaak betwist, waarbij het vooral draait om de oorsprong en productie van biomassa. Het verbouwen van biomassa specifiek voor energie- en materiaaltoepassingen neemt land in beslag en kan direct of indirect veranderingen van landgebruik veroorzaken. De nadelen van het verbouwen van biomassa zorgen voor extra aandacht voor restbiomassa: biomassa die niet specifiek voor de markt wordt verbouwd maar een bijproduct is van andere activiteiten. Eén van deze activiteiten is vegetatiebeheer in rivierlandschappen. Hoge en dichte vegetatie verkleint de waterafvoer capaciteit van uiterwaarden en verhoogt het overstromingsrisico. In dichtbevolkte rivierlandschappen, zoals de Rijndelta in Nederland, wordt de vegetatie regelmatig beheerd om het risico op overstromingen in bewoonde gebieden te minimaliseren. De vrijgekomen restbiomassa wordt in toenemende mate als waardevolle grondstof voor de bio-based economie beschouwd. Echter, restbiomassa heeft meestal al een functie. Als grondstoffen voor nieuwe toepassingen worden gebruikt, kan de oorspronkelijke functie verloren gaan. De bijdrage van restbiomassa aan duurzaamheid moet dan zorgvuldig geanalyseerd worden.

In het licht van de voordelen, nadelen en beperkingen van de bio-based economie heeft dit promotieonderzoek twee hoofddoelen: ten eerste, om de relatie tussen duurzaamheid en de bio-based economie te verkennen, en ten tweede, om te onderzoeken in welke mate en onder welke omstandigheden restbiomassa bijdraagt aan duurzaamheid. Voor het laatstgenoemde werd restbiomassa die vrijkomt tijdens landschapsmanagement in riviergebieden gebruikt als case study. Overkoepelend beschrijft en bediscussieert dit proefschrift de verschillende keuzes die beïnvloeden of biomassa gebruik bijdraagt aan een duurzame toekomst.

**Hoofdstuk 2** beschrijft de resultaten van een systematische literatuurstudie over de zienswijze van wetenschappelijke literatuur op de duurzaamheid van de bio-based economie. Er blijkt veel aandacht voor duurzaamheid te zijn in het wetenschappelijke debat over de bio-based economie, maar de visies verschillen, variërend van positief tot negatief. Diverse trends en voorwaarden voor een bijdrage aan duurzaamheid worden bediscussieerd, bijvoorbeeld betreffende duurzame biomassa productie en efficiënt gebruik van grondstoffen. Het hoofdstuk concludeert dat de bio-based economie niet vanzelfsprekend duurzaam is. Diverse risico's en valkuilen moeten worden overwogen en vermeden.

Biogas is één van de voornaamste toepassingen van zowel geteelde als restbiomassa. Biogas speelt een belangrijke rol in zowel beleid rondom de bio-based economie als beleid rondom hernieuwbare energie. Dit resulteert in een competitie van twee beleidsdomeinen over beperkt beschikbare grondstoffen. **Hoofdstuk 3** analyseert hoe biogas aan beide beleidsdomeinen kan bijdragen. Het beschrijft een diepgaande analyse van de huidige praktijk van biogas productie, gebaseerd op interviews met belanghebbenden. Er wordt beredeneerd dat biogas productie aan zowel beleid voor hernieuwbare energie, als ook aan de doelstelling voor een bio-based economie kan bijdragen. Maar efficiënt gebruik van grondstoffen wordt op dit moment belemmerd door conflicterende beleidsdoelstellingen en instrumenten.

In **Hoofdstuk 4** worden de resultaten van een literatuurstudie over de duurzaamheid van restbiomassa gepresenteerd. Het bevat een beschrijving van de geschiedenis van biomassa vraag en aanbod en de consequenties hiervan op duurzaamheid. Ook de voor- en nadelen van restbiomassa gebruik worden bediscussieerd, met een focus op de mogelijke consequentie van een toepassingsverandering. Voordelen zijn onder andere het vermijden van landgebruiksverandering, reductie van afval en verhogen van de algehele grondstofefficiëntie. Uitdagingen van restbiomassa gebruik zijn een lagere kwaliteit door een hoge heterogeniteit, negatieve gevolgen van een verandering van grondstofgebruik en beperkte ruimtelijke beschikbaarheid, omdat restbiomassa een bijproduct van andere processen is. Dit hoofdstuk laat zien dat restbiomassa onder bepaalde voorwaarden aan duurzaamheid kan bijdragen, maar dat het geen panacee is. De voordelen van restbiomassa gebruik voor nieuwe toepassingen moeten het verlies van een voormalige functie compenseren. Restbiomassa vergt andere overwegingen dan gecultiveerde biomassa: in plaats van het land heeft hier de grondstof al een functie en een verandering van grondstofgebruik heeft consequenties. Diverse factoren moeten worden meegewogen om potentiële toepassingen van restbiomassa te beoordelen, inclusief het potentieel om broeikasgasemissies te reduceren, fossiele grondstoffen te vervangen, de verstoring van biogeochemische stromen te verminderen en milieuvriendelijke producten te produceren.

Restbiomassa die tijdens vegetatiebeheer in riviergebieden vrijkomt wordt door Nederlandse watermanagement organisaties, zoals Rijkswaterstaat, in toenemende mate als waardevolle grondstof in plaats van afval beschouwd. **Hoofdstuk 5** verkent deze perspectiefverandering. Het is gebaseerd op een brede analyse van vegetatiebeheer praktijken en gebruik van biomassa, aangevuld met interviews met medewerkers van watermanagement organisaties, die verantwoordelijk zijn voor vegetatiebeheer. De resultaten laten zien dat er een trend is onder watermanagement organisaties om duurzaamheid mee te wegen in de afweging tussen verschillende biomassa toepassingen. Nieuwe instrumenten om duurzaam gebruik van biomassa te bevorderen worden ontwikkeld en in aanbestedingsprocedures toegepast. Er zijn echter nog geen objectieve, eenvoudig te gebruikende ranking criteria. Dit maakt het voor belanghebbenden moeilijk om een weloverwogen keuze te maken en resulteert in beoordeling zonder wetenschappelijke grondslag. Deze situatie openbaarde een dilemma tussen evalueren gebaseerd op maatschappelijke waarde (inclusief duurzaamheid) en evalueren gebaseerd op kosten. In de praktijk werden waarde en kosten (schijnbaar onbewust) door elkaar gehaald en bleken kosten uiteindelijk van groter belang.

Eén van de belangrijkste factoren bij de vergelijking van verschillende biomassa toepassingen is de netto broeikasgasemissie. In **Hoofdstuk 6** worden de resultaten van een kwantitatieve studie gepresenteerd, die de broeikasgasemissies van dertien restbiomassa toepassingen vergelijkt. De berekeningen houden rekening met zogenoemde contrafeitelijke scenarios, bijvoorbeeld de emissies die worden bespaard door met een biomassa toepassing een fossiel product te vervangen. Dit hoofdstuk laat zien dat broeikasgasemissies van toepassingen wezenlijk verschillen en, afhankelijk van de gekozen toepassing, beduidende winsten behaalt of lasten veroorzaakt kunnen worden. Het hoofdstuk concludeert dat de broeikasgasemissies van verschillende toepassingen vergeleken en meegenomen moeten worden in beleidskeuzes. Rekening houden met contrafeitelijke scenarios blijkt cruciaal, wat zowel de producten omvat die worden vervangen als huidige functies van restbiomassa. Het hoofdstuk laat zien dat de bio-energie toepassingen die werden beschouwd over het algemeen meer broeikasgas bespaarden dan de huidige materiaaltoepassingen. Het valt op dat dit haaks staat op het gevoel dat de meeste belanghebbenden in de praktijk hebben.

**Hoofdstuk 7** bediscussieerd de resultaten en conclusies van alle hoofdstukken in het licht van de keuzes die beïnvloeden of (rest)biomassa gebruik bijdraagt aan een duurzame toekomst. Kiezen voor biomassa in plaats van fossiele grondstoffen is een veelbelovende manier om een 'groene keuze' te maken die de negatieve consequenties van ons consumptiegedrag vermindert. Maar de resultaten van dit proefschrift laten zien dat een keuze voor biomassa niet automatisch zorgt voor een bijdrage aan duurzaamheid. De bio-based economie kan een belangrijke rol spelen, maar duurzaamheid moet de belangrijkste overweging zijn. Bovendien zijn de keuzes voor grondstoffen en toepassingen cruciaal.

Het kiezen van restbiomassa als grondstof kan een duurzaam alternatief voor geteelde biomassa zijn. Maar dit proefschrift laat zien dat restbiomassa vaak al een functie vervult en dat de consequentie van een verandering van toepassing beoordeeld moet worden. Restbiomassa is bovendien een uitdagende grondstof, bijvoorbeeld wat ruimtelijke beschikbaarheid en kwaliteit betreft. Restbiomassa is een bijproduct van andere processen en de beschikbaarheid kan niet makkelijk worden vergroot. Het is daarom niet praktisch om mogelijke toepassingen van restbiomassa los te zien van het aanbod. Waar restbiomassa beschikbaar is en in potentie van grote maatschappelijke waarde kan zijn, meer nog dan het traditionele gebruik, is het nuttig om verschillende toepassingen te vergelijken.

Dit proefschrift laat zien dat de waarde van biomassa in de praktijk een belangrijke rol speelt voor de keuze van restbiomassa in plaats van geteelde biomassa. Producenten van energie en materialen zijn in toenemende mate geïnteresseerd in minder aantrekkelijke, slechter beschikbare en slechter verwerkbare biomassa, waaronder ook veel restbiomassa valt. Maar dit komt niet doordat de biomassa duurzamer is, het ligt eraan dat het vaak goedkoper is. Biomassa eigenaren verwachten dat de waarde van restbiomassa in de toekomst zal stijgen, maar de resultaten van deze studie duiden erop dat restbiomassa in de nabije toekomst waarschijnlijk niet veel in waarde zal stijgen. Bio-based producten staan in competitie met fossiele producten en producenten kunnen niet meer voor de grondstoffen betalen, vooral als de restbiomassa meer voorbewerking nodig maakt.

De resultaten van dit onderzoek, specifiek **Hoofdstuk 6**, laten zien dat biomassa toepassingen verschillende uitkomsten hebben. Om een 'groene keuze' te maken zouden daarom toepassingen moeten worden gekozen gebaseerd op hun bijdrage aan duurzaamheid. Tijdens het vergelijken van verschillende toepassingen zou duurzaamheid de kern van alle ranking methodes moeten zijn. Het wordt aanbevolen dat methodes worden ontwikkeld die de meest efficiënte toepassing van biomassa bronnen definiëren. De studie laat zien dat duurzaamheidsanalyse van biomassa toepassingen als belangrijk wordt ervaren, maar zelden wordt uitgevoerd in de praktijk, omdat het tijds- en kosten intensieve analyses zijn.

Beleidsmakers wordt aanbevolen om te prioriteren tussen de maatschappelijke waarde van verschillende toepassingen. Hiervoor zijn drie overwegingen van groot belang. Ten eerste zou moeten worden overwogen of een biomassatoepassing een belangrijk probleem oplost. Ten tweede zou moeten worden geanalyseerd of duurzame alternatieven bestaan die niet op biomassa gebaseerd zijn. Ten derde moet er geëvalueerd worden in welke gevallen biomassa door nieuwe eigenschappen van producten aan duurzaamheid bij kan dragen. Beleid moet over verschillende sectoren en beleidsdomeinen worden afgestemd. Samen moeten beleidsmakers streven voor een optimaal gebruik van grondstoffen, zonder onder elkaar competitie over grondstoffen te veroorzaken. Daarnaast zou er ook meer worden nagedacht over hoe de bio-based economie en de circulaire economie elkaar kunnen versterken.

De bio-based economie is gerelateerd aan de ecologische, sociale en economische dimensie van duurzaamheid. Dit proefschrift focust op de potentiële levering van hernieuwbare grondstoffen en de voordelen die bio-energie en materialen kunnen hebben in vergelijking met fossiele grondstoffen. Dit heeft twee belangrijke kanten; aan de ene kant biedt biomassa de kans om niet-hernieuwbare grondstoffen te vervangen in de vervaardiging van producten en bij te dragen aan een duurzamere situatie. Aan de andere kant kan een verhoogde vraag naar duurzame producten ook een nadelig effect hebben: biomassa zou overmatig gebruikt kunnen worden, resulterend in dezelfde on-duurzame situatie die ooit het gebruik van het begrip "duurzaam" heeft veroorzaakt. Duurzaam beheer van ecosystemen en duurzame landbouw en bosbouw zijn nodig om biomassa de verschaffen. Dit proefschrift laat zien dat biomassa gebruik alleen bijdraagt aan een duurzame toekomst als biomassa duurzaam geproduceerd kan worden en verstandig wordt gebruikt.

## ZUSAMMENFASSUNG

Die intensive Nutzung von fossilen Rohstoffen für die Produktion von Energie und Materialien hat weitreichende, negative Folgen, unter anderem Klimawandel, Luftverschmutzung und die Verwüstung von Landschaften. Ein Ansatz zur Verringerung unserer Abhängigkeit von fossilen Energieträgern ist die Nutzung von Biomasse als organischer Rohstoff, wodurch ein Wandel von einer fossilen Wirtschaft hin zu einer Bioökonomie erreicht werden kann. Die Bioökonomie verspricht einen Ausweg vom Verbrauch fossiler Rohstoffe, ohne jedoch auf Konsumgüter verzichten zu müssen, die nun nachhaltig produziert werden können. Diverse wissenschaftliche Kontroversen und gesellschaftliche Debatten zeigen jedoch, dass Zweifel daran bestehen, wie realistisch ein solches Versprechen ist. In den letzten Jahren hat sich gezeigt, dass die Bioökonomie kein Wundermittel ist. Es hängt von vielen Entscheidungen ab, ob die Nutzung von Biomasse zu einer nachhaltigen Zukunft beiträgt, wie in **Kapitel 1** beschrieben. Die Annahme, dass Bioenergie Kohlenstoff-neutral sei, ist zum Beispiel umstritten, wobei die Diskussion sich vor allem um den Ursprung und die Produktion von Biomasse dreht. Der Anbau von Biomasse für die Energie- und Materialproduktion belegt Landwirtschaftsflächen und kann direkte oder indirekte Landnutzungsänderungen verursachen. Diese Nachteile von kultivierter Biomasse lenken die Aufmerksamkeit auf Restbiomasse: Biomasse, die nicht direkt für den Markt produziert wird, sondern ein Nebenprodukt von anderen Aktivitäten ist. Eine dieser Aktivitäten ist z.B. Landschaftsmanagement in Flussgebieten. Hoher und dichter Bewuchs verringert die Wasserabfuhrkapazität von Flussauen und erhöht das Hochwasserrisiko. Aus diesem Grund wird in dichtbevölkerten Flussgebieten, wie dem Rheindelta in den Niederlanden, die Vegetation regelmäßig bewirtschaftet, um das Risiko von Überflutungen zu reduzieren. Die Restbiomasse, die dabei entsteht, wird zunehmend als wertvoller Rohstoff für die Bioökonomie betrachtet. Allerdings erfüllt Restbiomasse oftmals bereits eine Funktion. Werden die Rohstoffe für eine neue Anwendung genutzt, kann die ursprüngliche Funktion verloren gehen. Die Nachhaltigkeit der Restbiomassenutzung muss dann sorgfältig analysiert werden.

Vor dem Hintergrund der Vor- und Nachteile sowie der Einschränkungen der Bioökonomie hatte diese Doktorarbeit zwei Hauptziele: erstens, die Beziehung zwischen Nachhaltigkeit und der Bioökonomie zu erkunden, und zweitens, Bedingungen zu analysieren, unter denen die Nutzung von Restbiomasse einen Beitrag zur Nachhaltigkeit liefert. Für das letztere Ziel wurde Restbiomasse aus dem Landschaftsmanagement in Flussgebieten als Fallstudie betrachtet. Themenübergreifend beschreibt und diskutiert diese Doktorarbeit die unterschiedlichen Entscheidungen, die beeinflussen, ob Biomassenutzung zu einer nachhaltigen Zukunft beiträgt.

**Kapitel 2** beschreibt die Ergebnisse einer systematischen Literaturstudie über die Sichtweisen auf die Nachhaltigkeit der Bioökonomie in der wissenschaftlichen Literatur. Die Aufmerksamkeit für Nachhaltigkeit in der wissenschaftlichen Debatte über die Bioökonomie ist groß, aber die Sichtweisen reichen von negativ bis positiv. Diverse Trends und Bedingungen werden besprochen, wie zum Beispiel nachhaltiger Anbau und effiziente Nutzung von Rohstoffen. Das Kapitel schlussfolgert, dass die Nachhaltigkeit der Bioökonomie nicht selbstverständlich ist. Diverse Risiken sollten abgewogen und vermieden werden.

Biogas ist eine der wichtigsten Anwendungen von sowohl kultivierter als Restbiomasse. Biogas spielt eine wichtige Rolle in der Politik sowohl zur Bioökonomie wie auch zu erneuerbaren Energien. In der Folge ist eine Konkurrenz um verfügbare Ressourcen entstanden.

**Kapitel 3** analysiert, wie Biogas zu beiden Politikfeldern beitragen kann. Es beschreibt eine tiefgehende Analyse der heutigen Biogasproduktion, basierend auf Interviews mit Akteuren in der Praxis. Es wird geschlussfolgert, dass Biogas sowohl zu den Zielen einer Bioökonomie als auch den Bestrebungen für erneuerbare Energien beitragen kann. Eine effiziente Nutzung von Rohstoffen wird derzeit jedoch durch widersprüchliche politische Ziele und Instrumente behindert.

In **Kapitel 4** werden die Ergebnisse einer Literaturstudie über die Nachhaltigkeit von Restbiomasse präsentiert. Das Kapitel umfasst eine Beschreibung der Geschichte von Biomasse-Angebot und -Nachfrage und die Auswirkungen hiervon auf die Nachhaltigkeit. Darüber hinaus werden Vor- und Nachteile von Restbiomasse besprochen, fokussiert auf die möglichen Konsequenzen einer veränderten Rohstoffnutzung. Vorteile umfassen zum Beispiel die Vermeidung von Landnutzungsveränderungen, Reduktion von Abfall und allgemeine Verbesserung der Rohstoffeffizienz. Herausfordernd sind schlechtere Qualität durch höhere Heterogenität, negative Folgen einer veränderten Rohstoffnutzung und die räumliche Verfügbarkeit, angesichts der Tatsache, dass Restbiomasse ein Nebenprodukt von anderen Prozessen ist. Dieses Kapitel zeigt, dass Restbiomasse unter bestimmten Bedingungen zur Nachhaltigkeit beitragen kann, aber kein Wundermittel ist. Die Vorteile einer Nutzung von Restbiomasse für neue Produkte sollten die Verluste von ursprünglichen Funktionen kompensieren. Restbiomasse erfordert andere Abwägungen als kultivierte Biomasse: nicht die Nutzung von Landflächen, sondern die Funktion von Rohstoffen wird verändert. Verschiedene Faktoren sollten in der Beurteilung von neuen Anwendungen erwogen werden. Zum Beispiel das Potenzial Grünhausgasemissionen zu verringern, fossile Brennstoffe zu ersetzen, Störungen von biogeochemischen Strömen abzuschwächen und umweltfreundliche Produkte zu produzieren.

Niederländische Wassermanagement-Organisationen betrachten Restbiomasse, die beim Landschaftsmanagement in Flussgebieten entsteht, zunehmend als wertvollen Rohstoff statt als Abfall. **Kapitel 5** betrachtet diesen Perspektivwechsel. Präsentiert wird eine breite Analyse von Landschaftsmanagement und der Nutzung von Biomasse in der Praxis, ergänzt durch Interviews mit Mitarbeitern, die für das Landschaftsmanagement zuständig sind. Die Ergebnisse zeigen einen Trend unter Wassermanagement-Organisationen zur Berücksichtigung von Nachhaltigkeit bei der Bewertung von Biomasseanwendungen. Neue Instrumente zur Förderung von nachhaltiger Nutzung werden entwickelt und angewendet. Es fehlen jedoch objektive, einfach zu nutzende Bewertungskriterien. Das macht es für Akteure schwierig, eine informierte Entscheidung zu treffen, was wiederum zu Abwägungen auf Bauchgefühl führt. Es zeigt sich ein Dilemma zwischen einer Abwägung auf der Basis von Gemeinnutzen oder Kosten. In der Praxis werden Nutzen und Kosten oft durcheinandergebracht und wiegen Kosten letztendlich schwerer.

Einer der wichtigsten Faktoren beim Vergleich von verschiedenen Biomasseanwendungen sind Treibhausgasemissionen. In **Kapitel 6** werden die Ergebnisse einer quantitativen Studie präsentiert, die die Treibhausgasemissionen von dreizehn verschiedenen Anwendungen aus der heutigen Praxis vergleicht. Die Berechnungen berücksichtigen kontrafaktische Szenarien, zum Beispiel die Emissionen, die bei einem Ersatz fossiler Brennstoffe durch Biomasse eingespart werden. In diesem Kapitel wird gezeigt, dass sich die Treibhausgasemissionen verschiedener Anwendungen wesentlich unterscheiden und deutliche Gewinne aber auch zusätzliche Emissionen zur Folge haben können. Treibhausgasemissionen sollten daher verglichen und in die Entscheidungsfindung mit eingebunden werden. Die Berücksichtigung kontrafaktischer Szenarien ist von entscheidender Bedeutung, wobei sowohl Produkte, die ersetzt werden, als auch ursprüngliche Funktionen von Restbiomasse beachtet werden sollten. Das Kapitel zeigt, dass die betrachteten Bioenergie-Anwendungen im Allgemeinen mehr Treibhausgasemissionen einsparen als die heute verfügbaren Materialanwendungen. Dieses Ergebnis widerspricht dem Gefühl vieler Akteure in der Praxis, die oft eine Präferenz für Materialanwendungen äußern.

**Kapitel 7** diskutiert die Ergebnisse und Schlussfolgerungen aller Überlegungen in den vorherigen Kapiteln im Lichte der Entscheidungen, die den Beitrag von (Rest-) Biomasse zur Nachhaltigkeit beeinflussen. Die Verwendung von Biomasse an Stelle fossiler Rohstoffe ist eine vielversprechende Strategie um eine „grüne Wahl" zu treffen, die die negativen Folgen unseres Konsumverhaltens verringert. Aber die Ergebnisse dieser Dissertation zeigen, dass die Verwendung von Biomasse nicht automatisch zur Nachhaltigkeit beiträgt. Die Bioökonomie kann eine wichtige Rolle spielen, aber Nachhaltigkeit muss eine zentrale Rolle in der Abwägung von Maßnahmen spielen. Darüber hinaus sind auch die Wahl von Rohstoffen und Anwendungen Schlüsselaspekte.

Die Nutzung von Restbiomasse kann eine nachhaltige Alternative zu kultivierter Biomasse darstellen. Aber diese Dissertation zeigt, dass Restbiomasse häufig bereits eine Funktion erfüllt und dass die Konsequenzen einer veränderten Nutzung beachtet werden müssen. Restbiomasse ist darüber hinaus ein schwieriger Rohstoff zum Beispiel aufgrund ihrer räumlichen Verfügbarkeit und Qualität. Restbiomasse ist ein Nebenprodukt anderer Prozesse und die Verfügbarkeit kann nicht einfach erhöht werden. Es ist darum empfehlenswert, mögliche Anwendungen nicht getrennt vom Rohstoffangebot zu erwägen. Wo Restbiomasse verfügbar ist und die Nutzung einen potenziell größeren Gemeinnutzen haben kann als ursprüngliche Funktionen, ist es sinnvoll, verschiedene Anwendungen zu vergleichen.

Diese Dissertation zeigt weiter, dass der Wert von Biomasse in der Praxis eine wichtige Rolle bei der Wahl zwischen kultivierter und Restbiomasse spielt. Produzenten von Energie und Materialien interessieren sich zunehmend für die Nutzung von unattraktiven, schlecht verfügbaren und schlecht zu verarbeitenden Rohstoffen wie manche Restbiomasse. Allerdings liegt dies nicht an ihrer Nachhaltigkeit, sondern an ihrem günstigeren Preis. Dagegen erwarten Biomasse-Besitzer, dass der Preis von Restbiomasse in der Zukunft steigen wird. Die Ergebnisse dieser Studie lassen schlussfolgern, dass der Wert von Restbiomasse in naher Zukunft wahrscheinlich nicht sehr steigen wird. Bio-basierte Produkte stehen in Konkurrenz mit günstigeren fossilen Produkten und Produzenten können daher nicht mehr für Rohstoffe zahlen, vor allem wenn die Biomasse in aufwendigen Prozessen vorbereitet werden muss.

Die Ergebnisse dieser Studie, im Besonderen **Kapitel 6**, zeigen, dass Biomasseanwendungen unterschiedliche Folgen haben. Um eine „grüne Wahl" zu treffen, sollten daher Anwendungen gewählt werden, die zur Nachhaltigkeit beitragen. Beim Vergleich verschiedener Anwendungen sollte deshalb Nachhaltigkeit ein zentraler Bestandteil von Beurteilungskriterien und -instrumenten sein. Es wird empfohlen, Methoden zu entwickeln, die die effizientesten Anwendungen von Biomasse definieren. In der Praxis wird eine Nachhaltigkeitsbeurteilung von Biomasseanwendungen als wichtig erfahren, jedoch selten ausgeführt, da sie sehr zeit- und kostenintensiv ist.

Politischen Entscheidungsträgern wird empfohlen, Prioritäten für Anwendungen zu setzen, basierend auf ihrem Gemeinnutzen. Drei Aspekte sind hierfür von großer Bedeutung: erstens sollte beurteilt werden, ob eine bestimme Biomasseanwendung ein relevantes Problem löst; zweitens sollte festgestellt werden, ob nachhaltige Alternativen, die nicht auf Biomasse basieren, verfügbar sind; und drittens sollte evaluiert werden, in welchen Fällen Biomasse-basierte Produkte durch neue Eigenschaften einen Beitrag zur Nachhaltigkeit liefern können. Maßnahmen über verschiedene politische Domänen sollten abgestimmt werden. Politische Entscheidungsträger sollten gemeinsam nach einer optimalen Nutzung von Rohstoffen streben, wobei Konkurrenz untereinander zu vermeiden ist. Darüber hinaus sollte weiter darüber nachgedacht werden, wie die Bioökonomie und die Kreislaufwirtschaft sich gegenseitig stärken können.

Sowohl die ökologische, soziale und ökonomische Dimension von Nachhaltigkeit sind für die Bioökonomie von Bedeutung. In dieser Dissertation liegt der Fokus auf der Lieferung erneuerbarer Rohstoffe und den Vorteilen, die bio-basierte Energie und Materialien im Vergleich zu fossilen Rohstoffen haben können. Hiermit sind zwei wichtige Aspekte verbunden: auf der einen Seite bietet Biomasse die Chance, nicht-erneuerbare Rohstoffe zu ersetzen und zu einer nachhaltigen Situation beizutragen. Auf der anderen Seite kann eine erhöhte Nachfrage nach nachhaltigen Produkten auch einen nachteiligen Effekt haben: Biomasse könnte übermäßig genutzt werden, wodurch eine nicht-nachhaltige Situation entsteht, die ähnlich der ist, die ursprünglich den Begriff „nachhaltig" ausgelöst hat. Biomasse sollte durch nachhaltigen Umgang mit Ökosystem und nachhaltiger Land- und Forstwirtschaft produziert werden. Diese Dissertation zeigt, dass Biomassenutzung nur zu einer nachhaltigen Zukunft beiträgt, wenn die Biomasse nachhaltig produziert und weise genutzt wird.


Floodplain of Bemmel, The Netherlands (S. Pfau)

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En natuurlijk Jenny. Meine beste Freundin, mijn taalmaatje, my personal advisor. Du hast mein ganzes Studium als mein huisgenootje miterlebt, wir hatten unsere ups- en downs und doch ist alles goedgekomen. Zum Glück! Deine Freundschaft bedeutet mir unheimlich viel und ich habe viel von dir gelernt. Egal ob doe-cadeaus in die Mikrobenausstellung, Harry Potter tentoonstelling oder een dagje wellness – mit dir kann ich über alles reden, lachen und schweigen. Danke, dass du für mich da bist!

*Familie*

Lieve schoonfamilie, ik wil jullie bedanken voor jullie interesse in mij en mijn onderzoek en alle geduld met mijn drukke bestaan de afgelopen jaren. Fijn dat jullie in de buurt zijn en ik onderdeel van jullie families mag zijn! En Ineke, Ferry en Mechtilde, bedankt dat jullie in de laatste paar maanden af en toe op Benjamin hebben opgepast, zodat ik de laatste loodjes kon leggen om mijn proefschrift af te maken en de verdediging voor te bereiden. Ik kijk ernaar uit om deze speciale dag met jullie te vieren!

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Detail nicht stimmte. Wir dachten immer, dass du bestimmt mal 100 Jahre alt wirst und wenn ich hätte wetten sollen, wäre ich mir sicher gewesen, dass du bei meiner Verteidigung noch dabei bist. So müssen wir uns damit begnügen, uns in Liebe an unsere begeisterte und fröhliche Oma zu erinnern.

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Erfahrung wäre ich nicht so, wie ich heute bin. Und ohne das Selbstvertrauen und Durchsetzungsvermögen, dass ich beim Segeln gewonnen habe, hätte ich es glaube ich auch nicht geschafft, diese Arbeit zu Ende zu schreiben. Auch außerhalb des Segelns habt ihr mich immer machen lassen. Ob es darum ging mit welcher Fremdsprache ich anfangen wollte, welche Fächer ich gewählt habe oder was ich studieren würde – ich habe immer alles selber entscheiden können. Ich danke euch von Herzen für diese Freiheit und euer Vertrauen in mich.

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Swinda


Herbaceous floodplain vegetation (W. van Iersel)

# About the author

Curriculum Vitae

Publications

Portfolio

Swinda Pfau was born in Essen (Germany) on November 8, 1987. In 2010, she completed her bachelor in Biology and in 2012 she received her MSc. degree in Environmental Sciences and Water Management from Radboud University Nijmegen and University Duisburg-Essen. She conducted the research for her master thesis in the context of Interreg IVA project Green Gas[1] and later continued in this project for her PhD research. In the first two years, she focussed on the link between the bioeconomy and sustainability in general. Later, she started working within NWO-TTW project RiverCare.[2]
Her background in water management helped her to combine her research on biomass use with the RiverCare topic of self-supporting river systems. During her time as PhD candidate, Swinda supervised several master student projects. Since 2015, she teaches and coordinates a master course on the bioeconomy for students with a natural sciences or management background. Since 2015, Swinda combined her PhD research with a job as consultant at Biomass Technology Group (BTG) in Enschede, where she continued to work after finalising this thesis.

## Publications in peer-reviewed journals

Pfau, S.F., Hagens, J.E., Dankbaar, B., and Smits, A.J.M. (2014) Visions of sustainability in bioeconomy research. *Sustainability*, 6(3), 1222–1249.

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[1] http://www.groengasproject.eu/Home.html
[2] https://kbase.ncr-web.org/rivercare/projects/project-h2a/

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### Reports

Hagens, J.E., Pfau, S.F., Smits, A.J.M. (2013) Evaluatie van IKS-project De Groene Hub 1.0 –Proces- en systeeminnovaties. Interreg IVA project Groen Gas, DELaND.

Pfau, S.F., Smits, A.J.M. (2014) Public Private Partnerships for decentralized energy landscapes. Interreg IVA project Groen Gas, DELaND.

## Courses

| Description | Institution | Year |
|---|---|---|
| Summer School: Governing the transition to a bio-based economy | ETH Zürich, Plant Science Center | 2013 |
| PhD course: Education in a Nutshell | Radboud University Nijmegen | 2013 |
| UTQ course: Effectieve individuele begeleiding van studenten | Radboud University Nijmegen | 2013 |
| PhD course: Academic Writing | Radboud University Nijmegen | 2014 |
| PhD course: Management voor Promovendi | Radboud University Nijmegen | 2014 |
| PhD course: Achieving your goals | Radboud University Nijmegen | 2014 |
| PhD course: Advanced Academic Writing | Radboud University Nijmegen | 2015 |
| PhD course: Grasping Sustainability | SENSE Research School | 2015 |

## List of abbreviations

bio-CCS – Bioenergy with carbon capture and storage
bio-LNG – biomass based liquid natural gas
cfl – Counterfactual
CHP – Combined heat and power
d – Day
DM – Dry matter
EEG – Erneuerbare Energien Gesetz
GCA – Grassy biomass composting for agriculture
GCG – Grassy biomass composting for growth media
GCHP – Grassy biomass CHP
GFi – Grassy biomass fibres
GFo – Grassy biomass fodder
GGG – Grassy biomass green gas
GGS – Grassy biomass grazing sheep
GHG – Greenhouse gas
GLG – Grassy biomass large grazers
GLS – Grassy biomass left on site
h – Hour
ha – Hectare
iLUC – indirect land-use change
kt – Kilotonne
LCA – Life-cycle assessment
LUC – Land-use change
MJ – Mega joule
NL – Netherlands
QDA – Qualitative Data Analysis
RED – Renewable Energy Directive
RUC – Resource use change
SOM – soil organic matter
t – Tonne
TJ – Tera Joule
tkm – Tonne kilometre

$t_{wb}$ – Tonne wet biomass
WCHP – Woody biomass combined heat and power
WH – Woody biomass heat
WLS – Woody biomass left on site