SHORT ROTATION WOODY CROPS FOR BIOENERGY
A FINANCIAL,
ENERGETIC AND
ENVIRONMENTAL PERSPECTIVE

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

1 Overall context of energy supply and global climate change

One of the most important challenges faced by mankind in the 21st century is the mitigation of the climate change. Human activities have been increasing the atmospheric concentrations of greenhouse gases (GHGs) and aerosols since the pre-industrial era. These GHGs capture the long-wave radiation emitted by the earth, and their increases are currently warming up the global mean surface temperature with 0.2°C per decade [1]. Among the GHGs carbon dioxide (CO_2) is a main agent in the greenhouse effect, because of its long residence time in the atmosphere and the large quantities emitted by human activities. Atmospheric CO_2 concentrations are rising quickly: the rate of atmospheric increase has been about 1.9 ppm yr^{-1} over the past decade [1]. Consequently, CO_2 concentrations had increased to over 390 ppm, or 39% above preindustrial levels, by the end of 2010, while the daily mean CO_2 concentration in Mauna Loa, Hawai, surpassed the symbolic mark of 400 ppm in May 2013 [2,3]. This rise is mainly due to GHG emissions from the combustion of fossil fuels, together with emissions due to human-induced land use changes and enhanced deforestation [1]. More than 56% of the global GHG emissions originate from the production and use of energy, and from transport (IPCC, 2007; 2011). Current global energy supply is for approximately 80% fossil fuel-based (coal, oil and natural gas) [4]. In addition to the disturbing impact of the GHG emissions from fossil fuel combustion on the climate of our globe, the unequal distribution of oil and natural gas over the globe leads to a high dependency of industrialized countries on imported fossil fuels. In 2010, the European Union imported more than 54% of its gross inland energy consumption from countries such as Russia, Algeria, and Saudi Arabia [5]. The political instability of some of these exporting countries poses a threat to a stable supply, thereby putting the energy security of the importing countries at risk.

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2 The contribution of bioenergy

Besides effectively reducing the consumption of fossil fuels through energy efficiency measures, an increased deployment of renewable energy sources is crucial to mitigate the current and future atmospheric CO_2 increase and to decrease the fossil fuel dependency. Bioenergy significantly contributes to the transition to a more sustainable energy mix. Biomass is currently the most important renewable energy source, accounting for about 10% of the global primary energy use of approximately 500 EJ per year [4]. Hydropower is the second-largest renewable energy source in primary energy use (~2%), followed by other renewable energy sources with a modest contribution of 1% [4].
Within the context of this dissertation, biomass is defined as 'the biodegradable fractions of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fractions of industrial and municipal waste' [6]. This variety of biomass resources are used to generate electricity and power, and to produce solid, liquid and gaseous fuels, making biomass the most versatile renewable energy source and an attractive petroleum alternative. Although biomass can be used to produce biochemicals and biomaterials substituting fossil resources, this dissertation focusses on the use of biomass for bioenergy only.
Currently, the majority (60%) of the biomass is consumed in traditional ways in the residential sector in developing countries for cooking and heating [2]. This – mainly unsustainable – use of biomass has a number of disadvantages as indoor air pollution and deforestation [7]. As modern energy carriers are gaining momentum, this relative share of traditional biomass is projected to decrease in the coming decades [8]. 'Modern' bioenergy involves the use of biomass for the production of electricity, heat and liquid and gaseous fuels with higher efficiencies than traditional carriers. Although the global use of modern biomass is smaller (20 EJ in 2008), it is rapidly growing and is expected to play a key role in the future energy supply [2,9–11]. Both the large (technical) potential of modern bioenergy (up to 500 EJ per year globally by 2050) and the projected reduction of production costs, underscore this expectation [12,13]. Additionally, biomass is an energy source that is almost CO_2 neutral – as the emitted carbon (C) during combustion was primarily absorbed in the biomass by photosynthesis during growth – if feedstock are produced sustainably and if efficient bioenergy systems are used [2,12]. Moreover, the substitution of fossil

fuel-derived energy constitutes a large and permanent CO_2 sink and contributes to the security of supply. Therefore, the European Commission has put a major emphasis on the deployment of bioenergy as a focal renewable source of energy for the European Union in its strategic communications on the Renewable Energy Road Map [14] within the framework of the Energy Policy for Europe [15].
Bioenergy can originate from many sources, from organic waste streams over forest residues to annual and perennial crops, grown specifically for energy production. The latter, primarily woody energy crops via short rotation coppice cultures, such as poplar and willow, are projected to play a major role in the supply of biomass feedstock [16,17]. Although estimates vary widely, dedicated energy crops are indeed attributed a high potential within the future bioenergy supplies [12,18].

3 Bioenergy from short rotation woody crops

The concept of short rotation coppice was initially launched in the 1960s in the USA and can be defined as carefully tended, high-density plantations of fast-growing perennial crops (lifetime: 20–25 years) for rotations between 2–10 years [19]. Several tree species have potential for short rotation coppice plantations, but fast-growing hardwoods with a high capability of coppicing, are the most promising [20]. The coppicing refers to the cutting of the trees at the base of their stump, resulting in the re-generation of new shoots from the stump and roots. Coppicing increases final biomass production [20,21]. Because of their fast growth and high yield, poplar *(Populus)* and willow *(Salix)* are the most widely used tree species in temperate short rotation coppice cultures [22]. The aboveground biomass of these short rotation woody crops (SRWCs) is collected at the end of each rotation cycle, generally after 2–5 years for poplar and willow, and can be used as a resource of renewable energy, paper pulp or fibers. Management of these SRWC plantations is on the interface between agricultural and forestry practices.
The cultivation of SRWCs for bioenergy was only stimulated in the 1970s during the OPEC oil embargo, in the search for alternatives to fossil fuels, and revived in the 1980s as a result of the set-aside policy of the European Union in times of agricultural overproduction [23]. More recently, concerns about climate change and energy security together with spectacular progress in tree genomics and biotechnology have generated renewed interest in SRWCs [10,17]. These scientific and biotechno-

logical advances awaken hopes that more productive and more suitable genotypes can be deployed in future SRWC cultures.

Although more than 85 million hectares of poplars have been recorded globally by the International Poplar Commission of the United Nations [24], the share of the plantations specifically dedicated to energy purposes is very small: only 0.9% of their total wood production (from poplar and willow) is used as fuel wood or as a resource of bioenergy. Existing poplar SRWC systems with the purpose to produce bioenergy are largely experimental. In Italy, the profitability and effects of environment, management regime and clones on biomass production are currently being evaluated for 4000 ha of poplar SRWCs scattered in the north and the middle of the country [25]. Unlike poplar, willow SRWCs for energy purpose have surged in the past decades, notably in Northern Europe, e.g. in Sweden about 16000 hectares have been planted to provide wood fuel for district heating schemes [26].

3.1 SRWC principles

To achieve maximal potential yields, SRWCs are preferably established on loam- or clay-containing soils with adequate water availability. Before planting, site preparation includes ploughing to assure good rooting and harrowing to even out the field. The field should be completely weed-free prior to planting either through chemical or mechanical weeding as SRWCs do not tolerate shade. Given the ability of most poplar and willow species to reproduce easily by means of asexual or vegetative propagation, SRWC plantations are usually established from un-rooted hardwood cuttings (Figure 1.1). These cuttings are harvested from one-year old or older stems during the dormant season and their size generally ranges from 20 to 30 cm.

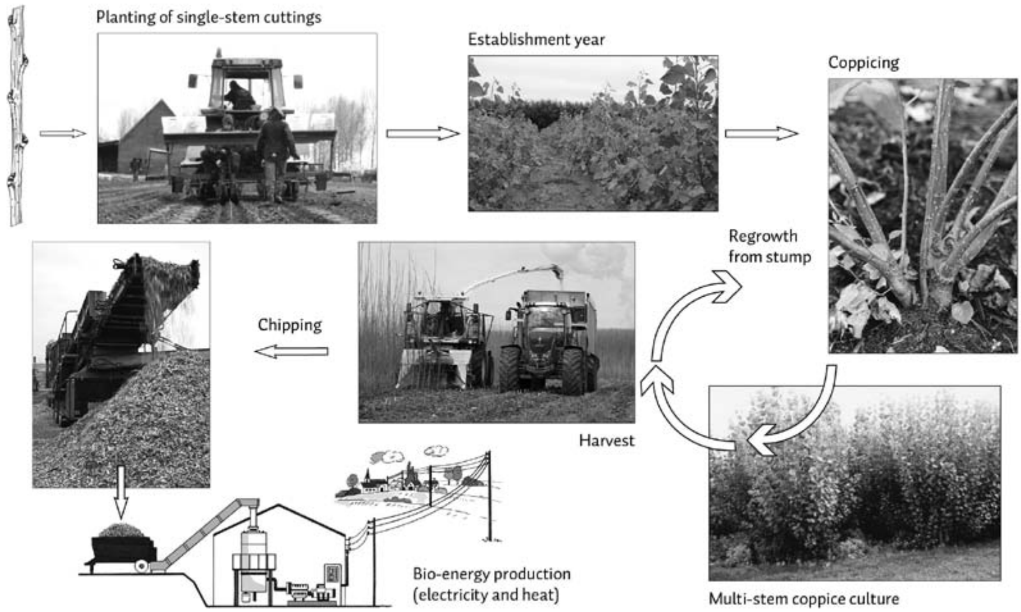

Figure 1.1 Short woody crops for bioenergy: concept

A distinctive feature of SRWC plantations is their high planting density in order to reach the highest possible yields per unit area. In the Swedish SRWC scheme, originally set up for willow, cuttings are planted in a double-row design at an overall planting density of 10000–15000 cuttings per hectare [27]. A second model often used in Italy is characterized by a single-row design with 3 m between rows and 0.5–0.7 m between cuttings within a row, facilitating weed control and accommodating 6000–7000 cuttings per hectare [25]. The initial planting density determines the length of the rotation cycle and vice versa; the higher the planting density, the shorter the rotation cycle.

Careful inspection of the establishment of the cuttings during the first months of cultivation is needed for satisfactory yield levels. Overall, the survival rate of hardwood cuttings at the end of the establishment year is rather high, about 90% for commercial poplar clones [28–30]. SRWCs require mechanical or chemical removal of weeds during the first growing season, or each year after coppice, due to their high light demand. During the following years, the SRWCs attain sufficient height to prevent weed growth. Thus, establishment is the most critical phase throughout the complete life span of SRWCs. The trees are often coppiced at the end of the first growing season to create an easily harvestable multi-stem coppice and to benefit from the already existing root systems which are known to enhance growth in the subsequent rotation cycles (Figure 1.1) [31,32]. Compared to willow, poplar has a stronger apical dominance and its stools tend to produce less but larger shoots when coppiced [33,34]. Nevertheless, coppicing is thought to reinvigorate growth, at least in the early rotations of SRWCs, and obviously avoids replanting costs [35]. If possible, harvests take place in winter to take advantage of the frozen soils to enter the field sites with heavy tractors and harvesters, avoiding soil compaction, and to coppice after leaf fall so that nutrients left over in senescing leaves are recycled (Figure 1.1). Harvest of SRWCs is typically performed every 2–5 years. Out of necessity, harvests are postponed to spring in case soils are too wet in wintertime. Two different harvesting regimes can be applied: (i) the crop can be cut and chipped simultaneously in situ; or (ii) the crop is cut and the stems are chipped as a later operation [36,37]. The harvested biomass can be used as renewable energy resource either for the production of heat and electricity through (co-)combustion and gasification, or for liquid transport fuels through chemical fermentation or thermo-chemical conversion [38].

3.2 Case study – POPFULL

Although several experimental and operational SRWC plantations exist in Northern (mostly willow) and Southern Europe (mostly poplar), the number of operational SRWC plantations with poplar and willow in Western Europe is small [17]. In 1996 an experimental SRWC plantation with 17 poplar clones was established in Boom (Antwerp, Belgium) on a former waste disposal site, moderately polluted by heavy metals. The field site (0.5 ha) was planted at a density of 10000 hardwood cuttings per hectares according to a double-row design. A study based on data retrieved from this plantation [32] showed the need for long-term SRWC trials to assess the effect of ageing, multiple coppicing and presence of pathogens and weeds on productivity in order to identify the most suitable genotypes depending on the management regime and the life time of the plantation. Yields during the establishment year(s) are often not representative for future biomass yields as rooting problems and early plant development may give a wrong impression of which are the most suitable clones for a given SRWC plantation.

To provide a more comprehensive understanding of the carbon cycling, the long-term biomass yields, and the overall potential of SRWCs, a commercial-scale plantation of 18.4 ha was established on former agricultural land in Lochristi (East Flanders, Belgium) within the framework of the Advanced ERC Grant, POPFULL (http://webh01.ua.ac.be/popfull/). After soil preparation by ploughing, tillage and pre-emergent herbicide treatment, 25 cm long dormant and unrooted cuttings were planted with an agricultural leek planting machine between 7 and 10 April 2010 (Figure 1.1). Twelve poplar and three willow genotypes representing different species and hybrids were planted in a double-row planting scheme with alternating distances of 0.75 m and 1.50 m between the rows and 1.10 m between trees in the rows, corresponding to a planting density of 8000 cuttings per hectare. Plantation management was extensive, without fertilization or irrigation [39]. In February 2012, this plantation was harvested for the first time after a two-year rotation cycle, using three different harvesting machines.

All the observational data analysed in this dissertation were obtained from this POPFULL plantation. All the (agricultural) operations during the establishment, the maintenance and the harvest of the SRWC plantation were monitored and inventoried to compose the financial and energy balance. In addition, these data were combined with (i) GHG flux measurements carried out to calculate the net exchange of GHGs (CO_2, N_2O, CH_4) between the plantation and the atmosphere and, (ii) soil samples taken to estimate the changes in soil organic carbon content, to assess the GHG balance of the SRWC plantation adopting a life cycle assessment (LCA) approach.

3.3 Environmental performance

The potential large-scale deployment of SRWC plantations for bioenergy will undoubtedly have implications on a range of environmental issues, such as biodiversity, soil erosion, water use, GHG emission, etc. [17]. These environmental effects can be positive or negative, highly dependent on the previous land-use. The substitution of annual crops for perennial SRWCs will most likely have a beneficial impact on the soil erosion rate, nitrate leaching and biodiversity, given the lower intensity of SRWC cultivation [40–41]. However, if set-aside land and permanent grassland are replaced, these benefits are less explicit [40]. Additionally, the high water use of SRWCs may have a strong impact on the local fresh water availability and quality, limiting the viability of these crops in arid regions without irrigation [42,43].

Notwithstanding the importance of the inclusion of various impacts in the environmental assessment of SRWCs, this dissertation mainly focusses on the GHG emissions and the energy balance of these energy crops. A basic requirement of any (bio)energy system to be energetically viable is that the energy produced must be larger than the inputs of non-renewable energy required for the establishment and the operation of the system. Additionally, its emissions during the entire life cycle should be lower than those of the (fossil) alternatives, to be ecologically feasible. Many scholars [44–46] assessed and compared SRWCs from an energetic and environmental point of view using different approaches. Although these studies confirm the energetic and environmental viability of SRWCs for bioenergy, their numerical results vary widely depending on methodological assumptions and the chosen system boundaries. Since this GHG emissions reduction potential is one of the main reasons for promoting bioenergy, it is important to establish a standardized approach to analyse the GHG and energy balance of energy crops. Such a standardized approach would allow meaningful comparison across studies to identify the conditions and the chain designs that result in lower GHG emissions.

Both the GHG and energy balance of SRWCs are site- and region-specific, depending strongly on conditions such as the previous land-use, the soil type, the precipitation, etc. and the required plantation management (type and rate of fertilizers and herbicides, irrigation, etc.). Therefore caution is advised when extrapolating specific results and research based on operational scale field data is needed to quantify the extent of these environmental impacts under various conditions, in order to allow sound conclusions about the suitability of SRWCs.

3.4 Financial feasibility

In addition to a beneficial environmental impact, a positive financial balance is an important prerequisite for investments in, and thus the deployment of, SRWCs. The production costs of SRWCs for bioenergy involve (i) establishment costs (initial weed and pest control, soil preparation, (mechanical) planting, planting material and wildlife control); (ii) operating costs (land rent, on-going weed and wildlife control, soil fertilization and irrigation, harvesting, storage and transportation of the biomass product); and (iii) costs of processing and converting the woody biomass to heat, electricity or fuels. This dissertation focusses on the costs associated with the cultivation phase, i.e. establishment costs and operating costs, since the

majority of the input data needed for the calculation and analysis of these costs were obtained first-hand from the operation POPFULL plantation. This allows to limit the assumptions and to improve the accuracy of the financial assessment.
Only few scholars [e.g. 47,48] have studied the financial profitability of SRWC based on operational scale field data. These studies found that government support is a pre-requisite for the successful and profitable deployment of SRWCs for bioenergy in Italy [47] and the United Kingdom [48], and reported on minimum required support levels and biomass prices for their respective regions. However, regional differences in costs of production factors (labour, inputs and land), farming practices (irrigation, fertilization, etc.) and climatic conditions together with the omission of crucial variables impede an extrapolation of these results to other regions. Therefore, detailed analysis based on high quality data of operational scale SRWC plantations in different regions is required to determine the actual (regional) potential of bioenergy from SRWCs. Only when sufficient experimental evidence for the financial feasibility of bioenergy cultures and for their positive impact on the energy and GHG balance has been provided, the enhanced application of bioenergy as a partial replacement for fossil fuels is facilitated.

4 Aims and approach

The overall aims of the research described in this dissertation are to investigate the financial performance and the greenhouse gas and energy balance of SRWCs for bioenergy, and to illuminate the existing Flemish government support scheme for the promotion of electricity from renewable energy sources technologies. More specifically we address the following research questions:

I Which financial valuation methods are most appropriate to assess the financial feasibility of SRWCs as a bioenergy crop?
II What is the financial performance of SRWCs in different settings and regions?
III To what extent do SRWCs provide climate and energy benefits?
IV How does the Flemish government contribute to the deployment of RES-E technologies?

The overall approach to answer the above-mentioned questions is through a detailed financial analysis and a full LCA of SRWCs – including the main GHG emissions (CO_2, CH_4 and N_2O) – combined with a complete energy balance. Both the financial analysis and the LCA are based upon (i) a database constructed from existing and published experimental data, and (ii) observational financial and environmental impact data that were obtained from the commercial-scale operational POPFULL plantation in Lochristi. Additionally, the Flemish support scheme for the promotion of RES-E technologies is scrutinized to understand the barriers for the effective implementation of these technologies. This multi-level approach allows a more extensive framing of the output of the research.

5 Outline of the thesis

The research questions are addressed in chapters 2 through 6. As shown in Figure 1.2., chapters 2 and 3 assess the financial feasibility of the cultivation of SRWCs. The main focus of these chapters lies on the cultivation phase, excluding the conversion to electricity and heat. Chapter 4 evaluates the GHG and energetic balance of SRWCs for the production of electricity using literature data, while Chapter 5 calculates the GHG and energy benefits of bioelectricity from the SRWC plantation established within the framework of the POPFULL project (Figure 1.2). Chapter 6 makes the link to policy incentives and the required support for renewable energy, including bioenergy, in the Flemish setting.

Chapter 2 addresses research questions I and II by scrutinizing the existing data on the financial viability and on the production costs of bioenergy plantations of fast-growing poplars and willows in various countries and regions around the globe. By assembling the available information in the scientific literature about the financial performance of SRWCs, the analyses revealed which specific information is lacking in the existing dataset that was obtained from the operational field plantation in Lochristi. Moreover, the study distinguishes the various financial valuation methods used to evaluate the financial performance of SRWCs and highlights the major shortcomings and gaps of the studies, to discuss the impact of the different valuation methods and shortcomings on the results presented. Finally, suggestions are made to reduce the variability in the results, and the effect of government incentives on the financial viability of SRWCs is discussed.

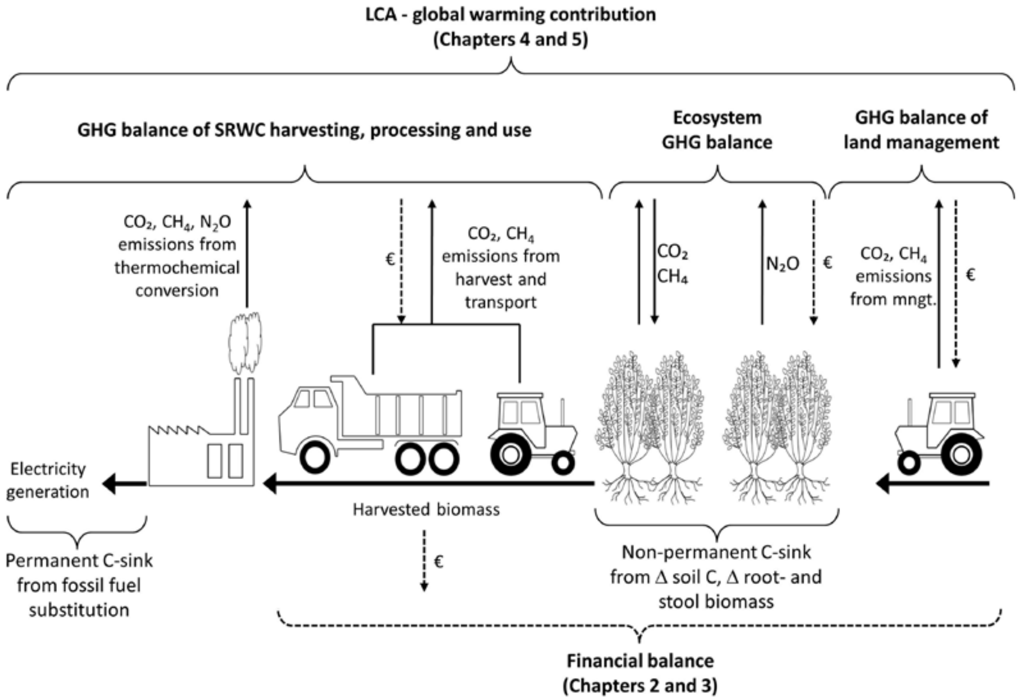

Figure 1.2 Graphical description of the short rotation woody crop supply chain and the boundaries of the different chapters within the overall framework of the wider POPFULL project

The findings from the previous chapter are used to develop a detailed cash-flow model (POPFINUA) to analyse the financial performance (i.e. the net present value, the equivalent annual value and the production costs) of the cultivation of poplar and willow in a SRWC management system for the production of woody biomass chips taking into account all relevant production factors. **Chapter 3** addresses research question II by presenting a case-study in which the newly developed model is used to assess the financial feasibility of the cultivation of SRWCs at the operational POPFULL plantation in Lochristi. Two base scenarios were simulated, one in which a farmer or an land owner uses his own equipment to cultivate the SRWC plantation (farmer's viewpoint) and one in which a farmer or an investor outsources all the activities related to the production of SRWCs (investor's viewpoint). For the first scenario all cost related to machinery (fuel, depreciation, etc.), labor and inputs were recorded meticulously at the POPFULL plantation and included in the POPFINUA model, while for the second scenario a specific cost per land area for each (agricultural) activity was included based on the costs for the respective activities charged by

Belgian contractors. This detailed model allows to alter a large number of variables and to simultaneously visualize the impact of the modification on the costs and on the financial viability of a SRWC plantation. This chapter examines the relative impact of key variables such as the discount rate, the biomass yield and price, and the subsidy level on the financial balance of the cultivation of SRWCs by means of a sensitivity analysis. Furthermore, three different harvesting strategies are studied and their effects on the financial profitability are discussed. This assessment reveals the most important contributors to the final costs together with the (non-) financial barriers to SRWCs in Belgium.

Chapter 4 addresses research question III through the analysis and synthesis of the available information in the scientific literature on the environmental impacts (mainly CO_2 and other GHG emissions) and the energy balance of SRWCs for the production of heat and electricity, including corrections for the assessment methodology used. The analysis provides essential data on (i) the energy ratio for the cradle-to-farm gate and the cradle-to-plant assessments, as well as (ii) values for the intensity of GHG emissions of the biomass production chain. In addition, various environmental impact assessment methods used in the literature thus far are compared and crucial methodological issues are identified. The chapter concludes with a number of suggestions for more standardized assumptions and the development of a widely accepted framework for the assessment of the energy balance and of the environmental impact of SRWCs for bioenergy to reduce the present substantial variability in results.

Starting from the lessons learned in the previous chapter, **chapter 5** addresses research question III by presenting a quantitative evaluation of the environmental impact of the production of electricity from SRWCs in Flanders. Most data used for the calculations presented in this chapter originated from the aforementioned POPFULL plantation. All relevant processes of bioelectricity production – from agrichemicals production, soil preparation, planting, weeding, harvest and chipping, to the final conversion of chips to electricity – and all required transportation within the system boundary are included. The environmental impacts included are the impacts on the GHG emissions during the life cycle and related to direct land use change, the energy requirement, and the land requirement. Additionally, a comparison of the GHG emissions of the investigated bioelectricity system to those of the EU non-renewable grid mix electricity generation (reference system), based on LCA modeling, is presented. Furthermore, the energy ratio and GHG savings of the bioelectricity system are calculated, considering two different technologies for the conversion of woody biomass chips to electricity (gasification and combustion).

Chapter 6 addresses research question IV by examining the 2013 reforms of the tradable green certificate scheme for the support of electricity generation from renewable energy sources in Flanders. This chapter evaluates whether the recent modifications to this support scheme provide adequate measures to tackle the shortcomings of the previous incentive scheme. The most important shortcomings were the high excess profits and the lack of qualification of renewable energy technologies. Since limiting the analysis to bioenergy only does not allow illustrating these shortcomings, the scope of this chapter includes all renewable energy sources and technologies of relevance for Flanders. To reveal some of the critical issues, a quantitative comparison with the German feed-in tariff scheme is presented, followed by suggestions to overcome these shortcomings.

Chapter 7 provides a general discussion of the results from the separate studies to address the main research questions and to present the final conclusions with regard to the financial, ecological and energetic performance of SRWCs as a renewable energy source.

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FINANCIAL ANALYSIS OF THE CULTIVATION OF POPLAR AND WILLOW FOR BIOENERGY

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Abstract

This paper reviews 23 studies on the financial feasibility and on the production/cultivation costs of bioenergy plantations of fast-growing poplars and willows (SRWCs), published between 1996 and 2010. We summarized and compared methods used thus far to assess the economics of SRWCs, identified the shortcomings and/or gaps of these studies, and discussed the impact of government incentives on the financial feasibility of SRWCs. The analysis showed that a reliable comparison across studies was not possible, due to the different assumptions and methods used in combination with the lack of transparency in many studies. As a consequence, reported production costs values ranged between 0.8 € GJ^{-1} and 5 € GJ^{-1}. Moreover, the knowledge of the economics of SRWCs was limited by the low number of realized SRWC plantations. Although specific numerical results differed, it became clear that SRWCs are only financially feasible if a number of additional conditions regarding biomass price, yield and/or government support were fulfilled. In order to reduce the variability in results and to improve the comparability across studies (and countries), we suggest the use of standard calculation techniques, such as the net present value, equivalent annual value and levelized cost methods, for the assessment of the financial viability of these woody bioenergy crops.

Keywords bioenergy crops, short rotation coppice, feasibility assessment, production costs, review

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1 Introduction

The energy issue is one of the major concerns of this century. The increasing global demand for energy, the limited reserves of fossil fuels and the urgent need to reduce the energy related emissions of greenhouse gases (GHG), have increased the interest in renewable energy sources which are potentially CO_2 neutral and can replace fossil fuels.

In order to mitigate climate change and to reduce the dependency on conventional fossil energy sources, the European Union has put forward the objectives to reduce GHG emissions by at least 20% and to obtain 20% of its total energy requirements from renewable sources by 2020 [1]. Within the framework of the Energy Policy for Europe [2] the European Commission has developed a Renewable Energy Road Map [3] with a major emphasis on the deployment of bioenergy as a key renewable source of energy for the EU. Not only at the European, but also at the national level bioenergy has been included in energy and climate policies [4]. Biomass is the only renewable energy source that can substitute for fossil fuels in all forms – heat, electricity and liquid fuels. In 2008 biomass supplied about 50 EJ globally, which represents 10% of the global annual primary energy consumption. This proportion could increase up to 33% of the future global energy mix by 2050 if the cost competitiveness of bioenergy improves, and if government actions remove constraints and/or provide incentives for bioenergy [5,6]. Such actions (or incentives) may influence the prices and improve the profitability of bioenergy. Estimates indicate that residues and organic wastes could provide between 50 EJ y^{-1} and 150 EJ y^{-1}, while the remainder would come from surplus forest production, agricultural productivity improvement and energy crops [5].

Under favorable conditions, the contribution of energy crops – i.e. the culture of short rotation woody crops (SRWCs) such as poplar (*Populus*) and willow (*Salix*) – can grow considerably, as these fast-growing plants present a great potential in the short term. Nevertheless, the implementation of SRWCs depends on several factors, such as the availability of the appropriate supply chain infrastructure, the degree of sustainability, and, last but not least, the financial feasibility of these energy crops [5]. A number of studies have focused on the wood supply chain and on sustainability issues of energy crops [7–9].

The large-scale deployment of SRWC plantations for the production of bioenergy would necessitate changes at the landscape-scale and in terms of land use, with an environmental impact depending mostly on what is replaced by these plantations. A substitution of annual crops for perennial SRWCs will most likely decrease the soil erosion rate, reduce nitrate leaching, and improve biodiversity [10,11]. Moreover, SRWCs require fewer biocides and fertilizer applications than other agricultural practices [12]. However, if set-aside land and permanent grassland are replaced, these benefits are less explicit [10].

On the other hand, the high water use of poplar may have a strong impact on the local fresh water availability and quality, and makes this crop less feasible for arid regions without irrigation [13,14]. Furthermore, it is important to avoid monocultures, since extensive planting of a single crop increases the risk for invasions of pests and diseases [15].

In addition to a beneficial environmental impact, however, a positive financial balance is an important prerequisite for investments in, and thus the further deployment of, these energy crops. The publications that have looked into the economics of this potentially promising renewable energy source have been scrutinized in this review, although their number is limited.

This study reviews and summarizes published studies on the financial feasibility and on the production/cultivation costs of bioenergy plantations of fast-growing poplars and willows. The overall goals are (i) to summarize and to compare methods used thus far to assess the economics of SRWCs, (ii) to identify the shortcomings and/or gaps of these studies, and (iii) to discuss the impact of government incentives on the financial feasibility of SRWCs.

2 Construction of literature database

For the literature source database construction, Thomson Reuters Web of Knowledge^{SM} and ScienceDirect® databases were searched for peer-reviewed journal articles published between 1996 and 2010 (i.e. the last 15 years) which reported (i) on the financial feasibility/viability/profitability, (ii) on the production costs, and/or (iii) on the cultivation costs of SRWCs, considering poplar and/or willow bioenergy plantations in particular. The titles and abstracts of more than 70 papers were analyzed to include only these papers which focus on the economics of producing poplar and/or willow consisting at least of a financial assessment of the cultivation phase of SRWCs. Studies which only included the conversion phase of biomass to energy, without properly stating the assessment methodology for the calculation of the biomass price (farm gate price) or without actually specifying the bioenergy source used, were not considered. On the other hand, studies that investigated both the production and conversion phases, and presented the assessment methodologies were included. Finally, 18 scientific publications were selected using the abovementioned criteria and from the reference lists of these papers, two reports [16,17], and one book chapter [18] were included as well. In addition, two articles [19,20], presented at the 16th and the 18th European Biomass Conference & Exhibition respectively, were considered. The inventory in Table 2.1 provides an overview of all studies included in the present review and of the main characteristics investigated. All values expressed in foreign currencies were converted into euros (EUR) using the average exchange rate of the year of publication retrieved from the European Central Bank (ECB) [21].

3 General analysis of the evaluated studies

Most reviewed studies (18 of 23) were undertaken in Europe, the remainder in America, i.e. four in North-America and one in South-America. About half of the studies (11 of 23) compared the financial feasibility of SRWCs with other agricultural activities, such as wheat, barley, upland sheep, etc., while seven studies made a comparison between SRWCs and other perennial and annual energy crops, or fossil fuels. Five studies performed a stand-alone study of SRWCs, without comparison.

Seven studies made a cradle-to-farm gate assessment, which means that the transportation up to the conversion plant and handling costs were excluded. One of these cradle-to-farm gate assessments [22] also presented the results of the cradle-to-plant gate stages, including transportation and handling costs. Eleven studies only evaluated the economics of SRWCs for bioenergy from cradle-to-plant gate, whereas one study [23] performed both a cradle-to-plant gate and cradle-to-plant assessment. This latter study involved the assessment of the capital and running costs of the conversion plant (i.e. electricity and heat). In addition, four studies reported separate results for all different stages, from cradle-to-farm gate, cradle-to-plant gate and cradle-to-plant (i.e. electricity or ethanol). Regarding the data, only six studies presented original data from an operational SRWC plantation, whereas the remaining studies used literature data in their analysis. Almost 80% of the evaluated studies simulated the presented

Table 2.1 Overview of 23 reviewed studies including the main objectives and conclusions of each study, as well as the calculated values and the calculation techniques employed

Country	Objectives of the study	Stages	Point of view
Belarus	Economic feasibility of willow SRWCs for energy on caesium-contaminated fields modeled using the Renewable Energy Crop Analysis Program (RECAP)	Cradle-to-plant gate Cradle-to-plant	F/PP
Belgium	Economic model to assess the profitability of willow SRWCs for small scale gasification and its sensitivity to several parameters	Cradle-to-farm gate Cradle-to-plant gate Cradle-to-plant	F/PP
Belgium	Comparison between willow SRWCs and two agricultural crops on metal-contaminated agricultural land based upon metal accumulation capacity, gross agricultural income per hectare, CO_2 emission avoidance and agricultural acceptance	Cradle-to-farm gate	F
Canada	Economic viability of bioenergy from poplar SRWCs on agricultural land using a bio-economic afforestation feasibility model	Cradle-to-plant gate	F
Chile	Assessment of the potential production costs of four cultivation regimes (*Populus, Salix, Eucalyptus and Pinus*) for energy	Cradle-to-farm gate	F
Czech Republic	Prediction of long-run marginal costs of biomass SRWCs for energy purposes (using an economic model) and evaluation of landscape function of SRWCs	Cradle-to-plant gate	F
Denmark & Sweden	Energetic, economic and ecologic balances of an integrated agricultural system compared to simple fallow on set-aside land	Cradle-to-plant gate	F
European Union	Calculation of production costs ranges and assessment of the main cost contributors of both annual and perennial energy crops in Europe, considering the costs of cultivation, land and risk	Cradle-to-plant gate	F
Ireland	Life cycle cost assessments to compare the production costs of Miscanthus and willow with conventional farming systems in Ireland	Cradle-to-farm gate	F

Calculation method	Calculated values	Data	Main conclusions	Reference
DCF (5% y^{-1}-10% $y^{-1\#}$) – EAV, IRR	ANM, IRR	L/M	Economic viability of willow SRWCs depends on potential yields (min. 6 Mg ha^{-1} y^{-1}), price of wood (min. dry mass price of 40 € Mg^{-1}) and harvesting method. Large-scale heat conversion systems are the most profitable, while electricity generation schemes are generally unprofitable	[23]
DCF (5% y^{-1}) – LC, NPV, EAV	PC, CNM, ANM	L/M	The interest rate, subsidies, the yield and the power of the generator have a large impact on the profitability of the project ceteris paribus, while the rotation length has a small influence	[40]
DCF (5% y^{-1}) – NPV	CGM	O	Due to the poor economics, willow SRWC is not likely to be implemented in Flanders in the short run without financial incentives despite its high potential as an energy and remediating crop	[28]
DCF (4% y^{-1}) – LC	PC	L/M	All studied scenarios, incl. those with a carbon incentive of 5 € Mg^{-1} CO_2eq, show higher delivered costs for biomass compared to low-grade coal, however large variations exist across the country	[36]
DCF (10% y^{-1}) – NPV	PC, CPC	L/M	Eucalyptus and pine have significantly lower production costs compared to poplar and willow and can compete with fossil fuels under the assumptions of this study	[37]
DCF (9.2% y^{-1}) – n.s.	PC	O/M	Knowledge of economics of SRWCs is limited due to low number and short period of real SRWC plantations and unavailability of a mechanized harvester	[30]
DCF (7% y^{-1}) – NPV	CGM	L	Combined food and energy systems can be beneficial from both farmers' and social point of view	[38]
DCF (6% y^{-1}) – EAV	PC	L/M	The calculated energy crop production costs are considerably lower for perennial SRWCs (4 € GJ^{-1} - 5 € GJ^{-1}) compared to annual straw crops (6 € GJ^{-1} - 8 € GJ^{-1}) and perennial grasses (6 € GJ^{-1} - 7 € GJ^{-1}), however, the first have higher costs of risks and require the largest changes at farm level	[45]
DCF (5% y^{-1}) – LC, EAV	PC, APC, AGM	L/M	Energy crop cultivation is highly competitive with conventional agricultural systems, however, government support can reduce prevailing investment risk considerably	[29]

Country	Objectives of the study	Stages	Point of view
Ireland	Economic viability of willow SRWCs, comparison with the economics of grain production, lowland sheep and suckler cow production and identification of economic drawbacks of pioneer production in Northern Ireland	Cradle-to-plant gate	F
Ireland	Energetic, technical and economic potential of willow SRWCs, forest residues and sawmill residues for power generation	Cradle-to-plant gate†	F
Italy	Energetic, economic and environmental analysis of poplar SRWCs in the Po Valley area	Cradle-to-farm gate	F
Italy	Economic and energetic assessment of poplar SRWCs in the western Po Valley	Cradle-to-plant gate	F
Poland	Economics of growing willow on large farms and comparison of viability of growing willow to wheat and barley	Cradle-to-plant gate	F
Scotland	Economic comparison of SRWCs, SRF and upland sheep and the influence of several governments support schemes on the viability SRWCs and SRF	Cradle-to- farm gate	F
Scotland	Assessment of the commercial viability of non-food and biomass crops by investigating the market demand and price for the crops and identifying the barriers so as to develop recommendations for farmers and for future research	Cradle-to-farm gate	F
Spain	Economic viability of poplar SRWCs considering the entire chain, comprising production, transportation and electricity generation	Cradle-to-farm gate Cradle-to-plant gate Cradle-to-plant	F/PP
Sweden	Describing the main properties of willow wood, the production stages of willow SRWCs and the economic feasibility	Cradle-to-plant gate	F

Calculation method	Calculated values	Data	Main conclusions	Reference
DCF (6% y^{-1}) – EAV	PC, AGM	L/M	Willow SRWCs give a GM of 66 € ha^{-1} y^{-1} with mean dry mass yield of 12 Mg ha^{-1} y^{-1} and is compared favorably to cereal and animal production, if subsidies and land opportunity costs are excluded. The number of established SRWCs plantation in a country is inversely proportional to the local production costs	[31]
DCF (5% y^{-1}) – n.s.	PC	L	Due to the high production costs of willow SRWC, this crop is not competitive with fossil fuel based electricity without forestry grants	[25]
DCF (4% y^{-1}) - n.s.	PC, APC, ANM	O	Under the conditions described (fertile, irrigated soil, intensive management, rotation length of 5 y, and lifespan of 10 y) poplar is profitable in comparison with traditional crops and performs better than 2-years SRWCs plantations	[20]
DCF (n.r.) – LC	PC	O/M	Poplar SRWCs are very attractive from energetic point of view, but will only be economically feasible with government support or with an increase of biomass dry mass price to at least 77 € Mg^{-1}	[27]
DCF (6% y^{-1}) – EAV	PC, APC, AGM	L/M	Willow is an economically viable crop for relatively large farms in Poland and the productions costs are significantly lower compared to Western European countries, thanks to lower diesel, labor and fertilizer costs	[32]
DCF (3.5% y^{-1}) – NPV, EAV	CGM, AGM	L/M	Upland sheep are more profitable than SRF and SRWCs because sheep returns are annual and both SRF and SRWCs require significant initial investments for establishment, but government support has a major impact on SRWCs' viability	[17]
DCF (7% y^{-1}) – NPV, EAV, IRR	CEM, AEM, IRR	L/M	Increased establishment grants and wood selling prices improved the competitiveness of willow SRWCs lately; however at current high grain prices willow cannot compete with agricultural crops	[16]
DCF (4.75% y^{-1}) – NPV, EAV	PC, APC, CPC	L/M	Poplar SRWCs for electricity generation is an economically feasible option in Spain and the balance can be improved by selling CO_2 emission credits	[26]
DCF (6% y^{-1}) – EAV	AGM	L	Economics of willow SRWCs are comparable to those of conventional food crops, but the major concern is the establishment of a decent market for the wood fuel	[52]

Country	Objectives of the study	Stages	Point of view
UK	Summary of the results and observations of larger scale field trials with SRWCs	Cradle-to-plant gate	F
UK	Full economic assessment of willow SRWCs, including a brief sensitivity analysis in Wales	Cradle-to-plant gate	F
USA	Summary and comparison of production cost, supply curve, transportation cost studies considering switch-grass, poplar and willow	Cradle-to-farm gate Cradle-to-plant gate	F
USA	Evaluation of the economics of poplar for ethanol production and fiber systems including a sensitivity analysis	Cradle-to-farm gate Cradle-to-plant gate Cradle-to-plant	F/PP
USA, NY	Economic analysis of willow SRWCs for cofiring with coal making use of a costing model which allows for detailed accounting of all activities from the planting to the power generation with a focus on three different government support schemes	Cradle-to-farm gate Cradle-to-plant gate Cradle-to-plant	F/A/PP

Stages: P = production, C = conversion; Point of view: F = farmer, A= aggregator, PP = power plant; Calculation method: DCF = discounted cash flow analysis, NPV = net present value, EAV = equivalent annual value, LC = levelized cost, IRR = internal rate of return; Calculated values: PC = per energy or mass unit production costs, CPC = cumulative per area production costs, APC = annual per area production costs, CGM = cumulative gross margin, AGM = annual gross margin, CNM = cumulative net margin, ANM = annual net margin, CEM = cumulative enterprise margin, AEM = annual enterprise margin; Data: O = Original data, L = Literature; M = Modeled; n.r. = not reported; n.s. = not specified; MRF = Medium Rotation Forestry; #: 5% y^{-1} for the production phase and 10% y^{-1} for the conversion phase; †: For willow SRWCs only the production was considered as the price level of the biomass was too high to include an assessment of the power generation; §: 5% y^{-1} for the grower, 10% y^{-1} for the aggregator, and 15% y^{-1} for the power plant

Calculation method	Calculated values	Data	Main conclusions	Reference
DCF (n.r.) – EAV	CPC, AGM	O/M	Subsidies and grants together with a stable market are still necessary for SRWCs to compete with conventional crops and to become feasible at commercial scale	[46]
DCF (6% y^{-1}) – NPV	CGM	O/M	With a dry mass price of at least 57 € Mg^{-1} together with a dry mass yield of minimum 8 Mg ha^{-1} and a 40% government support for establishment costs, willow SRWCs are profitable and can compete with other crops	[19]
DCF (6.5% y^{-1}) – NPV	PC, CPC	L/M	Huge differences in energy crop production costs hamper a meaningful comparison, as these dry mass costs range from 21 € Mg^{-1} to more than 103 € Mg^{-1}, while transportation costs range from 5.2 € Mg^{-1} to 7.5 € Mg^{-1} for a haul distance of 40km	[22]
DCF (5% y^{-1}) – See section 4.2.5	PC	L/M	Yield increases together with adaptation of poplar to lower quality land (land is a major cost item) will decrease the production costs of SRWCs. However, due to the high costs of the conversion process, woody biomass cannot compete with cheap fossil fuels	[18]
DCF (6% y^{-1}-10% y^{-1}-15% $y^{-1\S}$) – n.s., IRR	PC, IRR	L/M	Incentives at the level of the grower and the power plant to appropriate the positive externalities of willow co-firing are needed to ensure the economic viability of SRWCs for bioenergy	[24]

data using different approaches, mostly by performing a sensitivity analysis to assess the impact of e.g. changing yield or biomass sales prices on the profitability of the cultivations. These simulations are marked as 'modeled' in Table 2.1.

As mentioned above, the present review focuses on studies that at least assess the cultivation phase of the SRWC culture, mostly from the perspective of the farmer. Four studies, however, added the conversion phase and studied these investments from the power plant's point of view. In addition, one study [24] presented an integrated analysis of the economics of power generation from cofiring SRWCs with coal, from the viewpoints of the farmer, the aggregator and the power plant. In this study, the aggregator serves as a facilitator for the collection of biomass wood from farmers and its delivery to the power plant.

4 Analysis of values and techniques

A wide range of financial values calculated with various techniques have been reported in the reviewed literature to assess the cost structure and/or the financial feasibility of SRWCs. First, the different values are summarized below. Next, the calculation techniques to achieve these values are discussed.

4.1 Calculated values

The values calculated in the reviewed studies can be roughly divided in two groups, those which only include the cost-items, and those which consider both costs and benefits. Studies aiming at comparing the cultivation costs of SRWCs with other energy crops or fossil fuels, only calculate the production costs without considering the overall profitability of the SRWC culture. Alternatively, studies performing a comparative analysis of SRWCs with agricultural activities or assessing the overall financial feasibility of a SRWC culture rather opt for the calculation of the profit margins.

4.1.1 *Production costs (PC)*

Nine of the 23 evaluated studies only calculated and reported the production/cultivation costs of SRWCs without considering the overall profitability of the bioenergy plantation. Six studies, however, reported both the production costs and the profit margins of the SRWCs (see section 4.1.2), whereas one study [24] presented the production costs (PC) in combination with the internal rate of return (IRR) (see section 4.2.4). The cultivation costs are expressed either as per unit land area costs, or per energy and/or mass unit costs (PC in Table 2.1). The first mentioned costs are either considered cumulatively, i.e. over the entire lifetime of the plantation, or converted to annuities (cumulative production costs, CPC and annual production costs, APC in Table 2.1).

Based on the information provided in the studies and on the assumptions made, we recalculated the biomass production costs to values expressed in EUR per GJ for 13 of the reviewed studies, as shown in Table 2.2. The production costs differ significantly among studies ranging from 0.8–5 € GJ^{-1}, but are generally significantly higher than the delivered cost of coal, i.e. 1.2 € GJ^{-1} [25]. As Figure 2.1 shows, only one study [26] reported production costs below the cost of coal, which can be explained by the low land rent costs, approx. 700 € ha^{-1} over the entire plantation lifetime of 16 years, and the low establishment costs, which sum up to approx. 700 € ha^{-1}. These values are very low in comparison with other studies reporting land rent costs between 100 and 400 € $ha^{-1} y^{-1}$ [27] and between 75 and 250 € $ha^{-1} y^{-1}$ [23], and establishment costs of 2632 € ha^{-1} [28] and 2173 € ha^{-1} [22].

The discrepancy between the other studies can be partly explained by the different cultivation techniques (e.g. chosen field operations, type and rate of herbicides/fertilizers), (assumed) yield, lifetime, and rotation length. However, no correlation was found between the production costs at one side, and yield, lifetime, or rotation length at the other side. This was to be expected, as the largest part of the variance is explained by the regional differences in costs of inputs and the difference in cost categories included in the estimates (partly dependent on the stages considered). Some studies [25,29] only included the variable cultivation costs (excluding land rent), while others [22,30] included all fixed and variable costs. These observations make an adequate comparison of the cultivation costs of SRWCs across studies nearly impossible. There was also a lack of transparency in several studies as they did not report which costs were taken into account.

Overall, costs related to establishment and harvest operations accounted for about 60% of the total cultivation costs [25,29,31]. These ranges apply to the Irish SRWC cultivations, but are consistent with the values presented by Ericsson et al. [32], Tharakan et al. [24] and Manzone et al. [27], for Poland (53%), the USA (69%) and

Table 2.2 Biomass production costs for different countries, including dry mass yield values, rotation length and calculation period

Stages	Country	Yield (Mg ha^{-1} y^{-1})	Production cost (€ GJ^{-1})	Species	Rotation length (years)
Farm gate	Belgium	12	3.97	Willow	3
Farm gate	Chile	15-25[a]	3.5–3.9	Willow	5
Farm gate	Chile	10-12[a]	4.1–4.4	Poplar	8
Farm gate	Ireland	8.8	1.7–2.6	Willow	3
Farm gate	Italy	18	3.27	Poplar	5
Farm gate	Spain	13.5	0.8–0.85	Poplar	5
Farm gate	USA	11.23	3.27	Willow	3
Farm gate	USA, NY	14.8[b]	1.5	Willow	3
Plant gate	Czech Republic	10	3.3	Poplar	3
Plant gate	European Union	9	4–5	Willow	3
Plant gate	Poland	9	1.4[c]	Willow	3
Plant gate	Ireland	12	2.8	Willow	3
Plant gate	Ireland	9	3.4	Willow	4
Plant gate	Italy	10	4.1–4.9[d]	Poplar	2
Plant gate	USA	16	2.3	Poplar	6

General remarks: All production costs expressed per mass unit were converted into production costs per energy unit, based on dry mass lower heating value of 18 GJ Mg^{-1} and 18.2 GJ Mg^{-1} for willow and poplar, respectively.

a Converted from yield expressed in GJ ha^{-1} y^{-1}, based on a higher heating value of 19.1 GJ Mg^{-1}

b Dry mass yield of 9.8 Mg ha^{-1} y^{-1} in the 1st rotation and 14.8 Mg ha^{-1} y^{-1} in the subsequent ones

c Converted from MWh into GJ, costs are lower thanks to lower costs of labor, diesel and fertilizers in Poland

d The higher the cultivation surface, the lower the production costs, in this case surfaces of 50 ha and 100 ha were considered

Calculation period (years)	Included costs	Reference
26	Fixed costs, variable costs, land rent	[40]
15	Variable costs, land rent	[37]
15	Variable costs, land rent	[37]
23	Variable costs	[29]
10	Variable costs, land rent	[20]
16	Fixed costs, variable costs, land rent	[26]
22	Fixed costs, variable costs, land rent	[22]
22	Variable costs, land rent	[24]
21	Fixed costs, variable costs, land rent	[30]
22	Fixed costs, variable costs, land rent	[32]
22	Variable costs	[32]
22	Variable costs	[31]
25	Variable costs	[25]
8	Variable costs, land rent	[27]
12	Variable costs, land rent	[18]

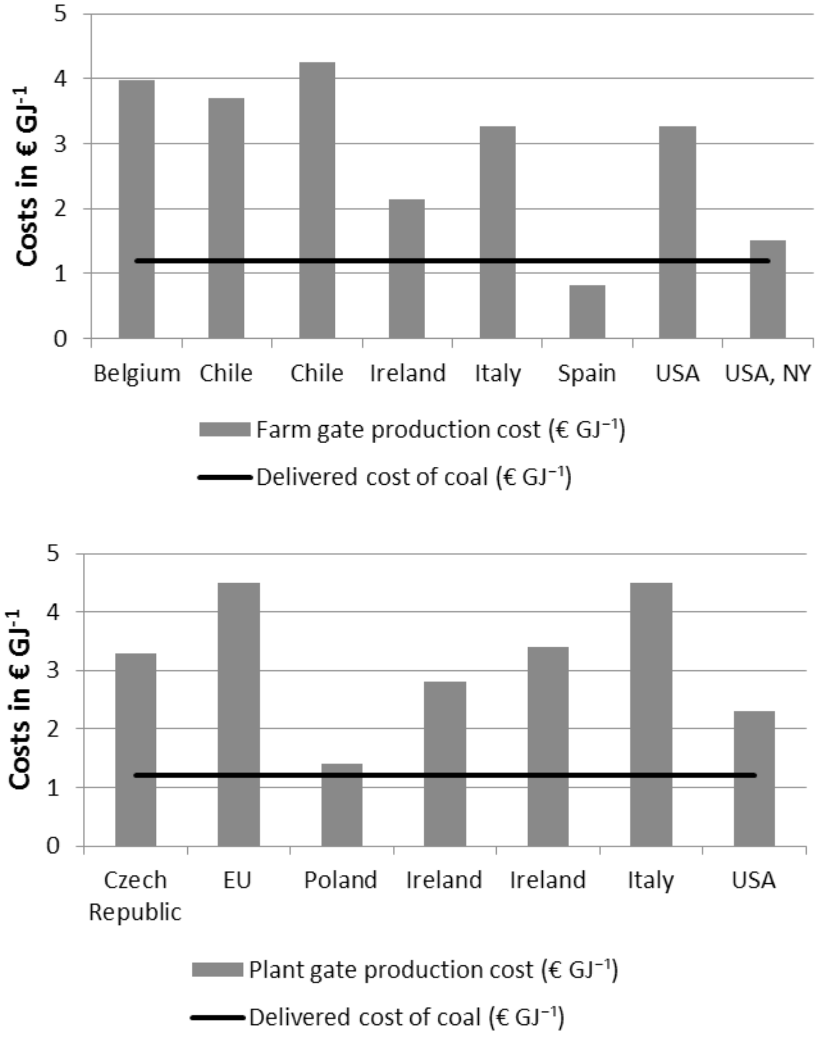

Figure 2.1 Farm gate (top figure) and plant gate (bottom figure) biomass production costs for different countries as compared to the delivered cost of coal based on data from Table 2.2

Italy (55%), respectively. Denmark and Sweden, however, benefit from economies of scale for the use of specialized planting and harvesting equipment, resulting in a lower contribution of these operations to the total costs, approx. 38% [32]. In addition, according to Styles et al. [29] stick harvesting is more expensive than combined harvest and chipping and increases the share of establishment and harvesting operations in the total cultivation costs up to 75%. Moreover, this harvesting strategy requires significant post-harvest chipping costs in a later phase, further increasing the preparation and handling costs. Chips, however, require substantial drying and storage costs as compared to cheap outdoor stick storage [29]. In addition, maintenance activities, such as fertilization and weed control, accounted for much of the remaining cultivation costs (excluding land rent). Unfortunately, only few papers provided a complete cost-breakdown of the different activities making an extensive description of the contribution of the different activities to the final cultivation costs impossible.

4.1.2 *Profit margins*

Thirteen of the 23 studies combined the production costs and the benefits through sales of biomass to calculate the profit margin necessary to assess the overall financial feasibility of SRWCs. Six studies reported the production costs and the margin values separately, while five authors only reported the margin values (e.g. [25]). In addition, two studies [16,23] reported margin values in combination with the IRR (see section 4.2.4). These margin calculations are divided in three categories, based on their inclusion or exclusion of various cost categories. First, the gross margin (GM) is defined as the revenues from the feedstock sold minus the variable costs for the production of the crop, excluding overhead costs, taxation, and interest payments. Secondly, for the calculation of the net margin (NM) the fixed costs allocated to the cultivation considered are also subtracted from the revenues [33]. The latter is also called the full cost approach, as it includes all costs (variable and fixed cash costs, and – if applicable – opportunity costs of owned resources) involved in the production of biomass feedstock. Despite the ostensible simplicity of the full cost approach, the calculations are far from easy to perform, in particular when overhead costs have to be allocated to the different debit items. Thirdly, the enterprise margin (EM) described by Bell et al. [16] includes crop related subsidy payments (revenues), contract charges (costs) and cropping related fixed costs in addition to the elements considered in the gross margin analysis while excluding all land related costs and revenues. These margins have also been divided in cumulative values, expressed in terms of per unit land area and annual values, in terms of per unit land area per year. In accordance with the production costs, a comparison of the profit margins across studies (and countries) proved to be meaningless. The inclusion of revenues to calculate the profit margins distorted the comparison even more severely, as these revenues are determined by the (assumed) wood chip prices and yield. The (assumed) retail prices differ significantly among studies and have a larger impact on the computed profitability than the yield, since a different wood chip price only has an influence on revenues, while a difference in yield also impacts the harvesting and transportation costs reciprocally [32]. The studies of Ericsson et al. [32] and Styles et al. [29] showed that a significant difference exists in wood chip prices across Europe: ranging from dry mass prices of 40 € Mg^{-1} in Poland up to 130 € Mg^{-1} in Ireland. In addition, one study [19] showed that a difference of only 12.5 € Mg^{-1} in biomass sales price, *ceteris paribus*, switched the SRWC plantation from loss-making to profitable. This proves the importance of the price assumptions on the profit margin and the uselessness of comparing profit margins assuming different wood sales prices.

4.2 Calculation techniques

Despite the above-mentioned differences in calculated values, all calculations have one feature in common: they all applied the discounted cash flow (DCF) approach. The perennial nature of SRWCs implies a delay of several years before the first harvest, and thus the first revenues. The DCF technique is therefore used to express future inflows and outflows of cash associated with a particular project in their present value by discounting so as to account for the effect of time [34]. This analysis is not only required to enable a comparison of the relative benefit of SRWCs with arable cropping, but also to assess the absolute profitability of these long-term cultures with lifetimes of 8 to 26 years.

The most important variable in the DCF analysis is the discount rate, as it determines the relative impacts of current and future costs and benefits. Increasing the discount rate, decreases the influence of future costs and benefits while increasing the impact of the early costs (i.e. establishment costs) on the final result. Generally, the nominal discount rate consists of a risk-free rate (mostly the yield on a long-term government bond in business economics) and a risk premium. This premium should be based on the combined factors of expected return and risks, i.e. the higher the risk, the higher the associated discount rate [35]. Some studies [17,32] have also incorporated the effects of inflation to calculate the real discount rate. In the reviewed studies about 80% of the discount rates ranged between 3.5% y^{-1} and 7% y^{-1}, with only one study using a discount rate higher than 10% y^{-1} [24]. This study used a high discount rate (15% y^{-1}) to assess the financial viability of a power plant co-fired with wood from SRWCs, and used lower discount rates (5% y^{-1} and 10% y^{-1}) to assess the production and aggregation phase, respectively. Some studies [36,37] provided the assumptions justifying the chosen discount rate, while others took a value from literature [25,38] or did not provide the provenance of the chosen rate at all [18,29]. The assumptions underlying the discount rate differ significantly among the reviewed studies. For instance, one study [32] took the discount rate of the national bank (5.5% y^{-1}), subtracted the inflation rate (0.8% y^{-1}) and added a risk premium (1.3% y^{-1}) to achieve a real discount rate of 6% y^{-1}, whereas another report [17] assumed a real discount rate of 3.5% y^{-1} to match the Treasury 'Green Book' requirements [39]. Several evaluation methods based on the DCF analysis were used in the reviewed studies; they are summarized below.

4.2.1 *Net present value (NPV)*

Several authors [17,38,40] used the NPV technique to calculate the production costs or the margin values of the bioenergy production activity over the entire (estimated) lifetime of the plantation. This NPV is the present value of the expected future revenues minus the present value of the expected future expenditures, with the costs and revenues discounted at the appropriate discount rate [34]. The calculated NPV can represent the cumulative gross, net or enterprise margin, but also the cumulative production/cultivation costs. In the latter case only the production/cultivation costs are considered without considering the overall profitability, and obviously the revenues are not taken into account (Eq. 1):

$$NPV = \sum_{t=0}^{n} \left(1+r\right)^{-t} \cdot A_t$$

with t = time (year) at which payment or revenues are made or received, n = lifetime of the plantation or calculation period, r = discount rate (dimensionless), and A_t = size of the incomes or expenses at time t. If both revenues and costs were taken into account, a positive NPV means that the project is profitable taking into consideration the assumptions about the discount rate, the retail price of the biomass, the yield, the plantation lifetime. Although the calculated cumulative values provide crucial information to decide upon the financial feasibility of a bioenergy project over the entire calculation period, most farmers prefer a financial value which facilitates a comparison with conventional annual crops. Therefore, various authors [16,31,32] calculated the annual values, using the equivalent annual value (EAV) technique.

4.2.2 *Equivalent annual value (EAV)*

From the NPV the equivalent annual value (EAV) can be computed based upon a model described by Rosenqvist [41]. This EAV enables a straightforward comparison between long-term (perennial) crops (such as SRWCs) and agricultural (annual) crops. This model uses both the present value and the annuity method to combine all costs (and benefits) into a single annual sum which is equivalent to all considered cash flows during the calculation period uniformly distributed over the entire period [41]. The formula is given in the equation below (Eq. 2):

$$EAV = \frac{r}{\left(1-(1+r)^{-n}\right)} \sum_{t=0}^{n} (1+r)^{-t} \cdot A_t$$

with r = discount rate, n = lifetime of the plantation or calculation period, t = time (year) at which payment or revenues are made or received, and A_t = size of the incomes or expenses at time t. The first right hand fraction of the equation represents the inverse of the annuity factor, whereas the second part is the NPV. In line with the NPV, the calculated EAV can represent the annual gross, net or enterprise margin, but also the annual production/cultivation costs.

4.2.3 *Levelized cost (LC)*

To calculate the production costs per energy or per mass unit of biomass, the IPCC suggests the use of the levelized cost (LC) method, a technique based on the NPV method [42]. The levelized cost of energy represents the cost of an energy generating system (in this case a SRWC plantation) over its lifetime. It is calculated as the price per energy unit or per mass unit at which the biomass feedstock must be produced from a SRWC plantation over its lifetime to break even [42]. Although this method is frequently used in the appraisal of power generation investments (where the outputs are quantifiable) [42,43], only few papers [27,29,36,40] have used this method to calculate the SRWC cultivation costs. The general formula for the levelized cost is given by Eq. 3 [42]:

$$LC = \frac{\sum_{t=0}^{n} (1+r)^{-t} \,.\, C_t}{\sum_{t=0}^{n} (1+r)^{-t} \,.\, Y_t}$$

This formula is derived of the adapted NPV formula (Eq. 4):

$$NPV = \sum_{t=0}^{n} (1+r)^{-t} \,.\, LC_t \,.\, Y_t - \sum_{t=0}^{n} (1+r)^{-t} \,.\, C_t$$

If we set the NPV equal to zero and explicitly assume a constant value for LC_t, this yields (Eq. 5):

$$LC \,.\, \sum_{t=0}^{n} (1+r)^{-t} \,.\, Y_t = \sum_{t=0}^{n} (1+r)^{-t} \,.\, C_t$$

which is a simple rearrangement of Eq. 3.
With n = lifetime of the plantation or calculation period, t = time (year) at which payment or revenues are made or received, r = discount rate, C_t = expenses at time t, Y_t = biomass yield at time t, and LC_t = levelized cost at time t.
Even though it appears as if the yield (a physical unit) is discounted, it is only an arithmetic consequence of the rearrangement of the NPV formula [43]. Following Eq. 3 the levelized cost equals the break even cost price of the produced biomass where the discounted revenues are equal to the discounted expenses.

4.2.4. *Internal rate of return (IRR)*

Three studies [16,23,24] calculated the IRR in addition to the production costs or the profit margins. The IRR is the discount rate which equates the present value of the expected revenues with the present value of the expected expenditures, i.e. the discount rate which gives a NPV of zero. Although this evaluation method is often used in business economics, its usefulness in agricultural economics is limited. Therefore, the IRR method was used in two studies [23,24] which have also taken the conversion phase into account. In both studies the IRR served as a common criterion to evaluate the investments of the aggregator and the power plant operator. The third study [16] only reported the IRR for the sake of completeness and mentioned that the high IRR (78%) is misleading and that it largely resulted from the low initial investments (thanks to establishment grants) rather than from high expected returns.

4.2.5 *Other practices*

Not all authors made use of the above-mentioned widespread calculation methods accurately. Strauss & Grado [18] adapted the levelized cost method to develop their own investment analysis method for SRWC plantations, which is characterized by the following formula (Eq. 6):

$$PC\left(\frac{\$}{odt}\right)=\frac{discounted\ \ establishment\ \ costs\left(\frac{\$}{ha}\right)+discounted\ \ maintenance\ \ costs\left(\frac{\$}{ha}\right)}{discounted\ \ yield\left(\frac{odt}{ha}\right)}$$

The harvesting and transportation costs, however, were added to the calculated production costs on a non-discounted basis, based on figures from [44]. This combination of discounted and non-discounted values creates a lot of confusion and is certainly not recommended. Other papers [32,45] have computed the per mass or energy unit production costs by dividing the EAV of the production costs by the average annual biomass yield instead of the annualized (discounted) yield or by dividing the NPV (which yields the cumulative production costs) by the undiscounted total biomass yield over the lifetime of the plantation. Moreover, the annual cost and margin values were not always calculated with the correct EAV technique. Some studies [26] conveniently divided the cumulative value calculated with the NPV method by the lifetime of the plantation to determine an annual value. However, in order to convert the present value of an irregular cash flow in fixed annual values over the entire calculation period, it is necessary to multiply the calculated cumulative values with the inverse of the annuity factor (as shown in Eq. 2).

Finally, several studies did not report their calculation method [25,30] or the discount rate [27,46] used; this less transparent approach makes any recalculation impossible.

5 Government incentives

In most of the studied countries, SRWCs for bioenergy are not financially viable without government incentives. Spain [26] and Poland [32] seem to be the only countries where subsidies and grants are of minor importance in the assessment of the financial viability of these energy crops.

As a consequence, almost all studies emphasized the need for active support mechanisms, such as establishment grants, and long-term stability of the status of energy crops at the national and international levels to ensure large scale adoption of SRWCs by farmers. This stability refers to a well-developed market for wood (chips) and stable conditions for energy crops in the European common agricultural policy (CAP) together with sufficient incentives for sustainable bioenergy from energy and environmental policy [32,46].

At the EU-level, energy crops which are grown on agricultural land registered under the Single Payment Scheme are eligible for annual subsidies of 45 € ha^{-1} under the EU Energy Aid Payment scheme [47]. Crops grown on set-aside areas are not eligible for this so-called carbon credit. Moreover, the farmer must have an agreement with a processing plant that will buy the harvested biomass, unless he is able to perform the processing himself [16,32]. Before 2007 these incentives were not fully available for the new EU member states.[1] They were intended to be gradually phased in over a period of 10 years, starting at 25% of the EU15 subsidy in 2004. This rate would increase by 5 percentage points in the first two years and by 10 percentage points thereafter [47,48]. As of January 1st, 2007, however, these subventions of 45 € ha^{-1} y^{-1} are made available to all EU member states under the same conditions [49]. Instead of opting for this carbon credit, a farmer can also decide to cultivate SRWCs on set-aside land and maintain set-aside payments, as SRWCs count as eligible crops under the Single Payment Scheme rules. The instability of these policies, however, restrains farmers from establishing SRWC plantations which require a long-term investment.

At the national level, the government incentives for energy crops differ significantly, with some countries (e.g. Belgium) providing no national incentives at all while others foresee establishment grants together with annual payments (e.g. Ireland) [29,50]. However, these support schemes change drastically over time. For example, in Scotland an establishment grant of about 1460 € ha^{-1} was available for SRWCs under the

1 The Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia and Slovakia.

old Scottish Forestry Grant Scheme up to December 2006 [17]. As of 2007, this support scheme was discontinued and replaced with significantly lower establishment grants under the Scottish Rural Development Programme (SRDP) of 40% of the actual establishment costs in non-less favored areas (non-LFA) and 50% of these costs in LFA, with a maximum total establishment cost of 2250 € ha^{-1} [16,17].
In the USA, on the other hand, a more stable support scheme exists where landowners can – under certain conditions – voluntarily enter into an agreement with the United States Department of Agriculture (USDA). Within this agreement they convert agricultural land to a permanent vegetative cover, such as SRWCs, to reduce soil erosion, to improve water quality, to establish wildlife habitat, and to enhance forest and wetland resources. In return, farmers are eligible for annual rental payments for the term of the multi-year contract (10–15 years). In addition, cost sharing is provided to establish the vegetative cover practices, with a maximum of 50% of the total establishment costs [51]. The annual rental payments differ across regions and over time; as an indication in the state of New York these rates were equal to approximately 80 € ha^{-1} y^{-1} in 2005 [24].

6 Concluding remarks and future perspectives

This review revealed that the estimation of the financial performance of SRWC systems based on the available literature is complex. Assumptions and experimental conditions differed among most studies, and various methods were used for the evaluation of the financial viability and/or the production costs of these bioenergy systems. Obviously, the techniques were chosen in function of the purpose of the study. Studies which aimed at comparing energy crops with traditional crops opted for the calculation of the annual profit margin rather than for the production costs, whereas papers including a comparative analysis with other fuels computed the (fuel) production costs. Moreover, there was a lack of transparency as several studies did not clearly state which cost categories were included and how the calculations were performed. These elements, together with the significant regional differences in government incentives, impeded a meaningful comparison among a large number of studies. Therefore unambiguous conclusions about the financial viability of SRWCs were difficult to be drawn. To reduce the high variability and enable future comparisons of the economics of SRWCs, we recommend the conse-

quent use of widespread standard calculation techniques, such as NPV, EAV or LC, instead of developing new methods specifically for perennial crops. Moreover, sufficient documentation should be provided in future studies to allow recalculations by interested readers.
There is an urgent need for more operational field data to enable an accurate assessment of the economics of growing SRWCs under different conditions. Most studies extrapolate and simulate data from few studies presenting original data, and further adapt yield and cost figures to the situation in the country considered.
In addition, more large-scale established SRWC plantations are needed to allow farmers to profit from economies of scale. The study of Rosenqvist & Dawson [31] showed that the production costs of SRWCs are inversely proportional to the established area of SRWC plantations. A farmer in Sweden, where about 15 000 ha of willow coppice are established, faces considerably lower planting and harvesting costs as compared to an Irish pioneer, where the first large-scale plantings were established in 1997 only.
Despite the wide variation in the results among the reviewed studies, it is clear that SRWCs in Europe and the USA were not financially viable, unless a number of additional conditions regarding biomass price, yield and/or government support were fulfilled.

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FINANCIAL ANALYSIS OF THE CULTIVATION OF SHORT ROTATION WOODY CROPS FOR BIOENERGY IN BELGIUM: BARRIERS AND OPPORTUNITIES

FINANCIAL ANALYSIS OF THE CULTIVATION OF SHORT ROTATION WOODY CROPS FOR BIOENERGY IN BELGIUM: BARRIERS AND OPPORTUNITIES

Abstract

This paper analyses the financial performance of a poplar short rotation woody crop (SRWC) plantation in Belgium, from a farmer's and an investor's viewpoint, based on simulations from the newly developed model POPFINUA. The establishment, production and harvest costs were investigated to calculate the net present value (NPV) and the equivalent annual value (EAV) of the SRWC cultivation when the biomass chips were sold at a price of 40 € Mg^{-1} with a moisture content (m.c.) of 50%. The calculated NPVs were 229 and -485 € ha^{-1}, and the EAVs equalled 16.3 and -34.6 € ha^{-1} y^{-1} for the farmer's and investor's scenario respectively. The break-even price at which the produced biomass could be sold at the farm gate excluding transport, handling, storage, and profit margins of the involved companies was calculated using the levelized costs (LC) method and equalled 78.4 and 83.5 € oven-dried ton $(odt)^{-1}$ for the farmer's and investor's viewpoint respectively. Three harvesting strategies, applied on a SRWC plantation of 18.1 ha in Flanders (Belgium), were studied and compared. It became clear that preference should be given to more economic, small-scale harvesters instead of large-scale self-propelled harvesters, given the relatively limited surface available for SRWCs in Belgium. Furthermore, the inclusion of transportation over a distance of 50 km by truck increased the LC by 15.1 € odt^{-1}. Moreover, subsidies such as establishment grants and/or yearly incentives proved indispensable to make this long-term investment profitable. This is particularly true for the scenario where an investor decides to cultivate SRWCs for energy purposes.

Keywords economic analysis, bioenergy crops, poplar, willow, feasibility/viability assessment

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1 Introduction

The use of fossil energy is widely considered as being harmful to the global environment by adding greenhouse gases (GHGs) to the atmosphere and by contributing to soil contamination and water pollution [1]. To mitigate these harmful impacts, the transition to renewable energy sources in combination with improved energy use efficiency is indispensable. Biomass has been identified as a renewable energy source which can contribute significantly to the carbon abatement strategy aiming at a 20% reduction and which can increase the share of renewable energy in the total energy consumption to 20% in Europe by 2020 [2]. Therefore, the European Commission has developed a Renewable Energy Road map for the deployment of bioenergy as a focal renewable source of energy for the EU within the framework of the Energy Policy for Europe [3,4].

Bioenergy can originate from many sources, from organic waste streams over forest residues to annual and perennial crops, grown specifically for energy production. The latter, in particular short rotation woody crops (SRWCs), such as poplar and willow, are projected to play a major role in the supply of biomass feedstock and are able to deliver 80–90% GHG emission reductions compared to the fossil energy baseline [5].

The present analysis fits within this overall framework of bioenergy sources from SRWCs, and their potential for the future energy supply in the EU, in particular from an economic point of view. The study aims at an assessment of the financial feasibility of bioenergy plantations of fast-growing woody crops, in this case poplars, in Belgium. We have opted to focus on the cultivation of poplar for bioenergy because this species is of significant value from an economic point of view in Belgium, covering about 13.8% of the forest area and accounting for up to 50% of the hardwood timber production [6]. Moreover, poplar has a number of well know favourable characteristics as compared to other energy crops. Poplars are easy to propagate from cuttings, they show a remarkable early youth growth and a high biomass yield, and they have an intensive gas exchange metabolism. Some drawbacks of this crop, on the other hand, are the considerable water and light demand, and the high susceptibility to diseases [7,8].

Several authors [9–11] have discussed the financial viability of SRWCs for bioenergy in a number of countries, with varying conclusions. Mitchell et al. [9] argued that government incentives and a stable market for wood chips are indispensable for SRWCs to compete with conventional agricultural crops and to become feasible at a commercial scale in the UK. Styles et al. [10] concluded that the cultivation of energy crops, such as willow and Miscanthus, is highly competitive with conventional agricultural systems in Ireland. Ericsson et al. [11], on the other hand, found that willow is an economically feasible energy crop for relatively large farms in Poland as the production costs are significantly lower compared to Western European countries, because of the lower diesel, labour and fertilizer costs.

Over the past years, a number of financial valuation models have been developed specifically for SRWCs. The budget model, EcoWillow, allows the financial assessment of the entire production chain for willow cultures in the USA [12]. EcoWillow, however, does not allow the modification of a number of parameters, such as the plantation lifetime and the harvesting strategy (only combined harvest and chipping is considered). Moreover, the model assumes coppicing after the first year to produce multiple stems, which is seldom applied when cultivating poplar because of its stronger apical dominance [1] [13]. Rosenqvist [14], on the other hand, developed a model which allows the comparison of the financial viability of long-term SRWCs with agricultural annual crops. Unfortunately, the model has been developed for Swedish conditions only and does not allow the modification of the discount rate, neither of the rotation length nor of the lifetime, making a contemporary and detailed financial analysis of the cultivation of SRWCs difficult. The Renewable Energy Crop Analysis Programme developed by the Energy Technology Support Unit on behalf of the UK Department of Trade and Industry is another example of a financial feasibility assessment tool dedicated to SRWCs [15]. Despite its apparent usefulness based on the description in the literature [16,17], all the efforts to secure a copy of this model were to no avail. A very useful and detailed, but unfortunately outdated model, is the ECOP model [18]. This model provides a highly detailed financial viability analysis of SRWC production and conversion stages, where electricity is produced in low power gasifiers. Although we were unable to acquire a version of this model, we were able to use several ideas of it [18].

The present study extends previous analysis (i) by discussing the financial viability of the cultivation of poplar SRWCs for bioenergy from both a farmer's and an investor's viewpoint based on data gained from the literature and from an operational plantation in Flanders, Belgium; (ii) by examining the relative impact of key variables (discount

1 Definition: Inhibition of the growth of lateral buds by the terminal bud of a plant shoot, i.e. the main central stem is dominant over the other side stems and as a consequence less shoots per stool are produced and the lower shoots are suppressed

rate, biomass yield, subsidies and biomass price) on the financial balance of the cultivation of SRWCs; (iii) by revealing the most important contributors to the final costs together with the (non-)financial barriers to SRWCs in Belgium.

2 Materials and methods

2.1 Model development

Because the afore-mentioned models did not allow a detailed analysis of the profitability of SRWCs, we developed a new spread sheet model 'POPFINUA' for poplar in a SRWC culture for bioenergy. The model is designed to analyse the financial feasibility of the cultivation of fast growing woody trees (i.e. poplar and willow) in a short rotation coppice management system for the production of biomass woody chips. The model allows us to alter a number of key variables and simultaneously visualize the impact of the modification on the costs and on the financial viability of a SRWC plantation. Moreover, the user can choose whether the operations are undertaken by farm labour or by contractors and include/exclude the transportation to the power plant (plant gate versus farm gate). The model was developed as a Microsoft® Excel® folder, which only contains functions and links between cells (without macros). In this analysis we only focus on the cultivation phase of SRWC plantation with or without including transport to the farm/energy plant. The model exists of four data input sheets, two balance sheets with discounted and non-discounted cash flows and a sheet containing the most relevant graphs. Figure 3.1 provides a simplified scheme of the model, including the model input and the output.

2.2 Model input

The model consists of four different data input sheets, of which one is dedicated to the input of general assumptions, such as the land area, land costs, assumed annual biomass increment in the first and subsequent rotations, discount rate, rotation length, number of rotations, plantation lifetime, overhead costs as a percentage of yearly costs, biomass sales price and government incentives (subdivided in establishment grants and yearly incentives). In addition, a number of options regarding the application of fertilizers and weed control can be modified in this sheet. The other three sheets are dedicated to the input of data regarding the establishment, maintenance, and harvest and transport.

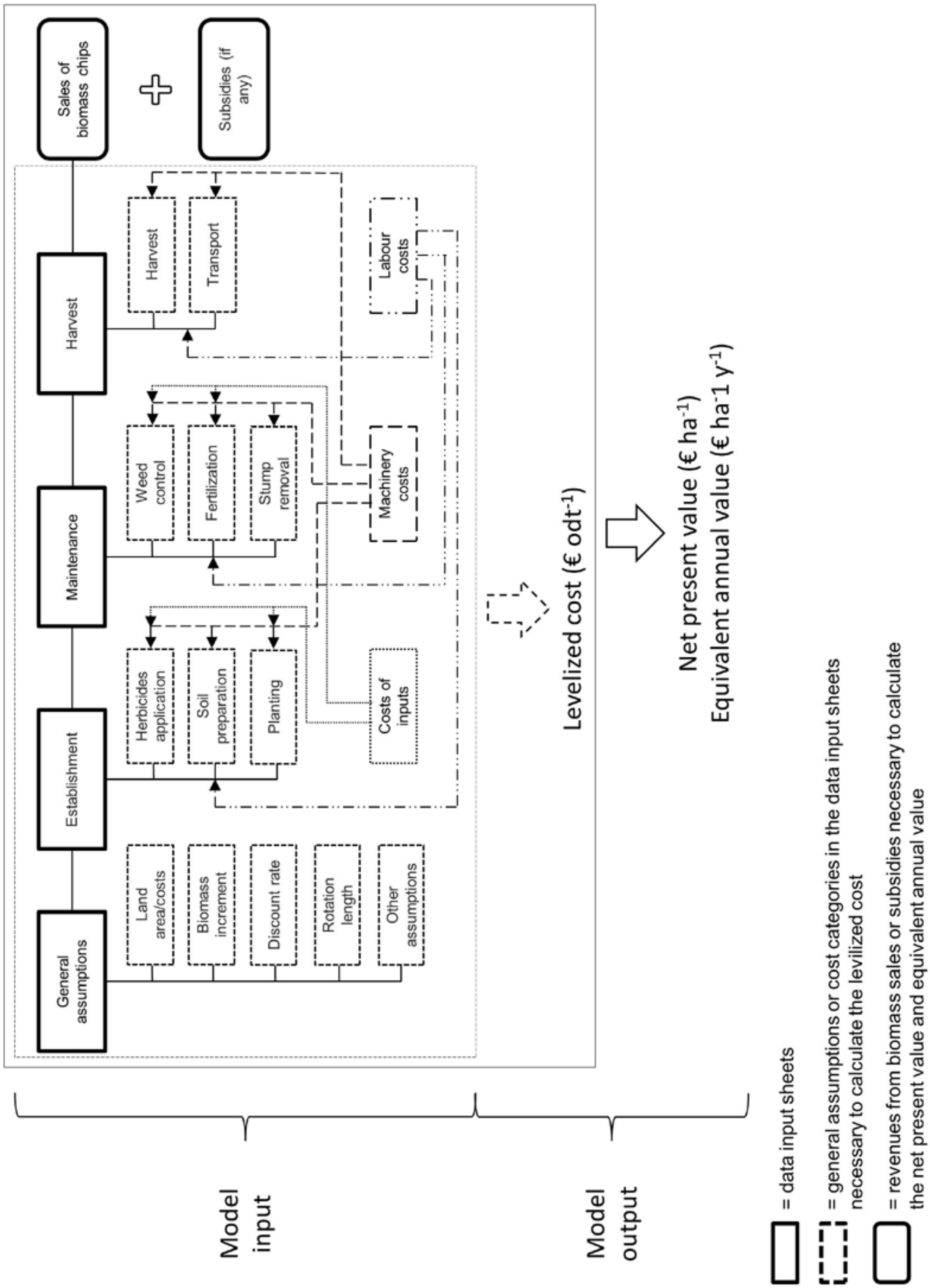

Figure 3.1 Schematic flow-chart of the POPFINUA model for the simulation/calculation of the financial balance of a short rotation woody crop plantation for bioenergy, the dotted lines with an arrow show which cost factors are required to calculate the full economic cost of the various agricultural operations

First, the establishment sheet uses input data regarding the site preparation, planting (including planting material) and herbicide application to calculate the establishment cost. For the calculation of the allocated costs of these agricultural operations, machinery costs, labour costs and costs of chemicals and planting material are required. The machinery costs are computed using the purchase price, salvage value, lifetime, fuel costs and transportation costs and are allocated to the agricultural operations based upon the operation rate of the machine for the operation involved. When the work is farmed out, however, data regarding the machinery and labour costs are not required and the user can simply fill in a value per hectare for the considered operation.
Second, three different weed management strategies are distinguished in the maintenance sheet: manual, mechanical and chemical weed control. The model allows the selection of one single or a combination of different weed management strategies, but does not allow the modification of the initial chosen strategy (and the associated costs) over the plantation lifetime. In addition, the maintenance sheet contains cells for the input of data regarding fertilizer application and stump removal at the end of the plantation lifetime.
Lastly, the harvest and the biomass transportation costs are calculated based upon data input in the harvest sheet. The model assumes no storage costs, as the biomass is sold as wet chips at the farm gate and stored at or close to the conversion facility, which implies that on-site storage is not required [12,18].
In accordance with the establishment, the user can either enter detailed data regarding the machinery, labour and material costs or decide to fill in a value per hectare if a contractor performs the maintenance and/or harvest of the SRWC plantation.

2.3 Model output

The model calculates three financial valuation metrics commonly used to calculate and assess the financial feasibility of long-term investments: the net present value (NPV), the equivalent annual value (EAV) and the levelized cost (LC). We did not calculate the internal rate of return, as this metrics can give a biased picture of the profitability of the plantation, certainly if establishment grants are taken into account [19].

2.3.1 *Net present value*

As the costs and benefits of the production of SRWCs are spread over the lifetime of the plantation, it is necessary to discount these items to allow a relevant comparison with competing investment projects. Therefore, the NPV of the SRWC plantation is calculated which brings back the cash flows to a reference time on the basis of a reference discount rate, following Eq. 1.

$$NPV = \sum_{t=0}^{n} \left(1+r\right)^{-t} \, . \, A_t$$

with t = time (year) at which payment or revenues are made or received, n = lifetime of the plantation or the calculation period, r = discount rate (dimensionless) and A_t = size of the revenues or expenses at time t. A positive NPV means that the plantation is profitable taking into consideration the assumptions about the discount rate, the retail price of the biomass, the yield, and the plantation lifetime (see also Table 3.1).

2.3.2 *Equivalent annual value*

Despite its undeniable interest from an investor's point of view, the practical usefulness of the NPV from a farmer's viewpoint is limited as it does not allow a straightforward comparison with traditional annual agricultural crops. As SRWCs are mostly planted on agricultural land and are therefore often in competition with agricultural crops, it is important to allow a relevant and accurate comparison on a yearly basis. Therefore, the model calculates the EAV, which combines the present value and the annuity method to convert all costs and benefits into constant annual amounts over the considered plantation lifetime, following Eq. 2.

$$EAV = \frac{r}{1-(1+r)^{-n}} \sum_{t=0}^{n} \left(1+r\right)^{-t} \, . \, A_t$$

with r = discount rate, n = lifetime of the plantation or calculation period, t = time (year) at which payment or revenues are made or received and A_t = size of the payment at time t. The first right-hand fraction of the equation represents the inverse of the annuity factor, whereas the second part is the NPV.

2.3.3 *Levelized cost*

A third metric, which is generated by the model is the levelized cost which gives the unique break-even cost price for the woody biomass chips where discounted revenues are equal to discounted expenditures, following Eq. 3:

$$LC = \frac{\sum_{t=0}^{n} (1+r)^{-t} . C_t}{\sum_{t=0}^{n} (1+r)^{-t} . Y_t}$$

with LC = levelized cost, n = lifetime of the plantation or calculation period, r = discount rate, C_t = expenses in year t and Y_t = biomass yield in year t. This metric is used to compare the cultivation cost of SRWCs with other energy crops/feedstock or other (renewable) energy carriers (if converted to a cost per energy unit).

Table 3.1 Summary of the general and the base case scenario assumptions of the POPFINUA model simulations of this study

General assumptions	Unit	Value
Land area	ha	18
Percentage of headland	%	20
Planted area	ha	14.5
Assumed biomass increment - 1st harvest (dry matter)	Mg ha^{-1} y^{-1}	4
Assumed biomass increment (dry matter)	Mg ha^{-1} y^{-1}	12
Land rental, lease or opportunity costs	€ ha^{-1} y^{-1}	250
Discount rate	% y^{-1}	4
Rotation length	y	3
Number of rotations		7
Plantation lifetime	y	21
Fuel price	€ l^{-1}	0.9
Biomass sales price at 50% m.c. (farm gate)	€ Mg^{-1}	40

m.c. = moisture content

2.4 Data collection

The estimates for SRWC costs and revenues used in this analysis are based on a mixture of observed costs gained from an operational 18.4 ha SRWC site (POPFULL) situated in Lochristi, Belgium (51°06'44" N, 3°51'02" E) and established in April 2010, supplemented with literature data for variables which could not (yet) be collected from the plantation. These included among others lifetime of the plantation, biomass yield in subsequent rotations, etc. For a more detailed description of the operational site and the different genotypes of poplar and willow planted on this site, we refer to Broeckx et al. [20]. Table 3.2 provides a general overview of the site characteristics.

Table 3.2 Site characteristics and climate conditions of the operational short rotation woody crop plantation in Lochristi, BE, this plantation provided input data for the POPFINUA model

Site characteristics	Latitude	51°06'44" N
	Longitude	3°51'02" E
	Elevation (above sea level)	6.25 m
	Topography	Flat
	Vegetation	*Populus* Spp. & *Salix* Spp.
	Soil type	Sandy with poor natural drainage
Climate conditions	Average annual temp.	9.5°C
	Average annual precipitation	726 mm

3 Financial analysis

3.1 Scenario assumptions

This study calculated the average, budgeted costs of production, based on a full economic costs approach, including all variable and the allocated fixed costs, both from an investor's and a farmer's point of view. Therefore, a rental value for land which is owned by the farmer and a charge for the farmer's own labour were included. Moreover, we assumed the same land costs for the farmer and the investor, to eliminate land as a determining variable for the different profitability of the two base case scenarios. These scenarios are based on 2010 prices and a discount rate of 4% y^{-1}. We calculated the discount rate by adding a risk premium of ± 1% y^{-1} to the nominal discount rate published by the European Commission for risk-free investments (3.07% y^{-1}) [21]. Furthermore, we assumed that the overhead cost represent a fixed fraction of 3% of the overall yearly cost (including land rent). These overhead costs include administration costs as well as allocated costs of buildings and infrastructure.

In this study, we assumed the application of a post-emergent herbicide (glyphosate) prior to planting to kill existing vegetation. Next, the soil was (mole) ploughed, harrowed and a pre-emergent herbicide was applied. After soil tillage and the application of herbicides, 25 cm long dormant and unrooted stem cuttings were planted in a double-row planting scheme, which implies an alternating distance of 75 cm and 150 cm between the rows and a varying distance between trees within the rows depending on the desired planting density. This double-row spacing facilitates the use of existing agricultural machinery for any necessary management operation. Regarding the cultivation, we assumed no fertilization during the lifetime of the plantation, as previous research on a 16-year-old SRWC plantation showed no decline of productivity after four rotations without fertilization [22,23]. Most of the nutrients in a poplar SRWC plantation are in the leaves and these are annually being returned and recycled to the soil [24–26]. Moreover, we assumed weed control to take place only in the establishment phase. We are aware that these optimistic assumptions had an impact on the costs and have therefore also calculated the cultivation costs when weed management is required in subsequent rotations (see section 4.3.6). An overview of the cost categories included and the management scheme assumed in this analysis are shown in Table 3.3.

Table 3.1 provides an overview of the general assumptions which were equal for both scenarios. Unlike a number of studies [11,27] we did not assume that the production of SRWCs has moved beyond the 'pioneering' stage, as this is not the case in Belgium yet. As a consequence, Belgian farmers and investors interested in cultivating these energy crops are penalized by the unavailability of the appropriate machinery for planting and/or harvesting.

3.2 Scenario 1 – Mechanization by the farmer

In this scenario a farmer produces SRWCs for bioenergy among other crops using his own equipment for agricultural operations, such as (mole) ploughing, harrowing, planting, spraying and collection of the chips during harvest. The harvest is subcontracted, as the costs of purchasing and owning a SRWC harvester are too

Table 3.3 Overview of cost items for the cultivation of short rotation woody crops for bioenergy during an assumed lifetime of 21 years with 3-year rotations [7,12,54]

Cost item/ plantation year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Post-emergent herbicide	Y																					
Soil preparation	Y																					
Pre-emergent herbicide	Y																					
Planting	Y																					
Weed control		Y		(Y)			(Y)			(Y)			(Y)			(Y)			(Y)			(Y)
Harvest				Y			Y			Y			Y			Y			Y			Y
Fertilization	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Stump removal																						Y
Land rent	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
General and over-head costs	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Y: included in the base case scenario; (Y): included in the scenario analysis; n.a.: not assessed high to be justified. The farmer remunerates himself for the hours he works on the plantation using the average hourly labour cost of 35 € h^{-1} in Belgium for the cost analysis [28]. The actual hours of labour generally exceed the field machine time because of maintenance and travel time. Therefore, we calculated the labour costs by multiplying the number of hours that the machine is used to perform a certain agricultural operation by 1.1, as suggested by Edwards [29] and as applied in earlier studies assessing the economic performance of bioenergy crops [30].

For the analysis from the farmer's viewpoint, we also took into account the farm machinery costs allocated to the different agricultural operations based upon the operation rate, which we measured at the POPFULL plantation (Table 3.4). We assumed the use of modern agricultural machinery for the cultivation of poplar SR-WCs. Although there are several differences in agricultural practices between the USA and Europe, we have used the recommendation of the American Agricultural Economics Association (AAEA) for the calculation of the maintenance costs of the agriculture equipment, as there were no reliable European data and recommendations available. We used the following formula for these calculations Eq. 4 [31]:

$$R = RF_1 \,.\, PP \,.\, \left(\frac{h}{1000}\right)^{RF_2}$$

with R = accumulated repair and maintenance costs (€), RF_1 = repair factor 1, RF_2 = repair factor 2, PP = purchase price (€) and h = accumulated machine use at the end of the lifetime (h).

For the calculation of the diesel consumption, however, we have not used the standardized methodology suggested by the AAEA, where the fuel use is calculated as a fixed fraction of the maximum power of the considered tractor. Alternatively, we have used the real fuel consumption rates (see Table 3.4), which differed depending on the operation performed, gained from the operational POPFULL plantation. Table 3.4 provides an overview of the costs of the agricultural machinery used for the cultivation of SRWCs.

3.3 Scenario 2 – Investor in SRWCs

In this scenario a company or an investor interested in cultivating energy crops to produce biomass chips rents land and appoints one or several contractors to carry out all the work at the plantation. This includes soil tillage, weed control, harvest

Table 3.4 Overview of the costs and characteristics of agricultural equipment used for the cultivation of short rotation woody crops [30,31,55] (Kristof Mouton, Groep Mouton bvba; personal communication); (Marc Verhoest, Verhoest Marc bvba; personal communication)

Machine	Purchase price (k€)	Use ($h\ y^{-1}$)	Lifetime (y)	RF1	RF2	Maintenance costs (€ h^{-1})	Lubricant use (€ h^{-1})	Salvage value (k€)	Fuel use ($l\ h^{-1}$)	Operation rate ($h\ ha^{-1}$)	Combined tractor
Tractor - 160 HP	135	800	12	0.007	2.0	9.1	0.307	36.45	n/a	n/a	
Tractor - 360 HP	200	800	12	0.007	2.0	13.4	0.603	54.0	n/a	n/a	
Subsoiler	7.5	125	20	0.28	1.4	3.0	n/a	1.95	19.0	1.0	160 HP
Plough	12	75	20	0.29	1.8	4.8	n/a	3.12	16.7	0.3	160 HP
Harrow	9.5	100	20	0.27	1.4	3.4	n/a	1.52	18.3	0.2	160 HP
Line cultivator	25	100	10	0.23	1.4	5.8	n/a	7.50	16.0	1.0	160 HP
Leek planting machine	12	150	10	0.32	2.1	6.0	n/a	4.80	6.1	0.9	160 HP
Rotary cultivator	66	150	10	0.36	2.0	35.6	n/a	19.8	25.0	2.0	360 HP
Spraying equipment	20	200	10	0.41	1.3	10.1	n/a	16.0	16.7	0.3	160 HP
Fertilizing equipment	8	100	10	0.63	1.3	5.0	n/a	3.2	17.0	n.a	160 HP
Trailer - $40m^3$	44	800	10	0.19	1.3	15.6	n/a	11.4	20.0	n/a	160 HP

HP: horse power; RF1: Repair factor 1; RF2: Repair factor 2; n/a: not applicable; n.a.: not assessed

Table 3.5 Overview of the costs for different agricultural operations for the cultivation of short rotation woody crops carried out by a Belgian contractor

Operation	Price range (€ ha^{-1})
Post-emergent herbicide	140–220
Pre-emergent herbicide	260–280
Mole ploughing	120–180
Ploughing	120–250
Harrowing	110–240
Planting	500–1000
Mechanical weeding	120–300
Fertilizing (300 kg N ha^{-1})	200–250
Stump removal	550–1700

and fertilizer application (if any). As a consequence, we did not estimate the operation cost of the machinery (as we did in the farmers scenario), but we based our analysis on prices provided by Belgian contractors that submitted a tender for a contract in the framework of the POPFULL plantation for which we invited tenders. Table 3.5 provides an overview of the range of rates that Belgian contractors charged for the different operations required for a SRWC plantation, showing considerable differences in charged rates among contractors.

4 Results and discussion

4.1 Base case scenario 1 – Mechanization by the farmer

Under the base case conditions, the investment in the plantation was profitable for a farmer after 21 years (Figure 3.2). This profit, however, was rather limited and amounted to 229 € ha^{-1} or 16.3 € ha^{-1} y^{-1}. The break-even dry matter price for biomass chips at the farm gate was 78.4 € Mg^{-1}. The harvesting costs made up 45% of the total discounted cultivation costs, while the general costs including land rent and overhead costs accounted for 37% of these costs. Establishment costs only contributed to the total costs for 16%, whereas maintenance costs barely made up 2% of the total discounted costs. This low share of the maintenance costs resulted logically from the assumption of little maintenance and no fertilization.

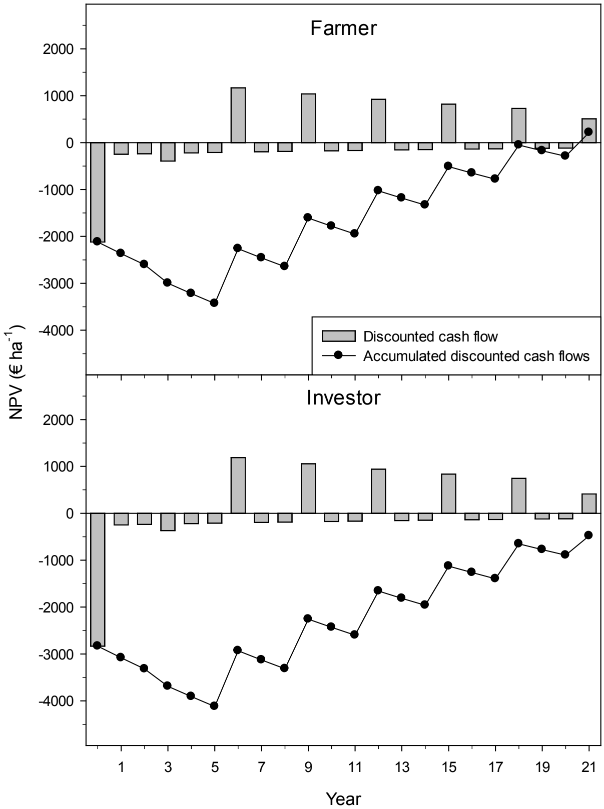

Figure 3.2 Simulated discounted yearly cash flows and accumulated discounted cash flow for farmer's (top panel) and investor's (bottom panel) base scenarios for a short rotation woody crop plantation with a three-year rotation and a total lifetime of 21 years

4.2 Base case scenario 2 – Investor in SRWCs

As opposed to the farmer's viewpoint, the cultivation of SRWCs was not profitable from an investor's viewpoint considering the base case assumptions. The NPV equalled -485€ ha^{-1} over the lifetime of 21 years and the EAV was -34.6 € ha^{-1} y^{-1}, while the required dry matter price for the woody biomass chips to reach a break-even amounted to 83.5 € Mg^{-1} (Figure 3.2). The contributions of the harvesting (42%) and general costs (35%) to the total discounted costs were lower than in the farmer's scenario, while the shares of the establishment costs (20%) and the maintenance costs (3%) were slightly higher. This is due to the higher costs for agricultural operations if the establishment and maintenance are subcontracted as compared to the farmer's own mechanization and labour.

4.3 Scenario analyses

A number of assumptions were made to calculate the financial balance of SRWCs in Belgium. To assess the impact of the most uncertain assumptions on the profitability of these energy crops, we carried out a number of sensitivity and scenario analyses. The results of these analyses are summarized below.

4.3.1 Biomass yield

The biomass yield is a crucial parameter in the financial performance of the SRWC plantation. In the base case scenario, we assumed a dry matter yield of 12 Mg ha^{-1} y^{-1}, which corresponds to the average values for poplar trees in a coppice culture under temperate European conditions, ranging from 10 to 15 Mg ha^{-1} y^{-1} [32–35]. Given the assumption that the SRWCs are planted on fertile agricultural land in Belgium (Stijn Overloop, Flemish Environment Agency; personal communication) and since breeding and selection programs to improve the yield and to decrease the susceptibility to rust and diseases are ongoing, there is a significant potential for yield improvements. Dry matter yields between 20 and 25 Mg ha^{-1} y^{-1} have been reported under optimal conditions [36,37]. These yield potentials are also backed by process-based models, accounting for the climatic conditions of Belgium, under the assumption that water and nutrients are not limiting and given that the SRWCs are established on soils with high agronomic potentials [38]. Biomass yields during the first rotation period, however, are significantly lower due to the plant's investment in root growth during early development [11,39]. For our calculations, we assumed a dry matter yield of 4 Mg ha^{-1} y^{-1}, which is the first rotation yield we measured on our POPFULL plantation.

The yield of SRWCs depends on both environmental variables (soil fertility, climate conditions, pathogen infections, etc.), and plantation management (weed control, fertilization scheme, etc.). Therefore, we performed a sensitivity analysis to assess the impact of a wide range of possible yield figures on the profitability of the plantation. We found that for both the farmer's and the investor's scenario, a dry matter yield of 11–13 Mg ha^{-1} y^{-1} is required to reach the break-even point (Figure 3.3). An increase in the biomass yield by only 25% (from 12 to 15 Mg ha^{-1} y^{-1}) would trigger a more than fivefold increase in the NPV over the lifetime, while decreasing the LC by 22%. The major impact on the NPV is explained by the twofold impact of the yield on both the costs and benefits. All the agricultural operations were charged

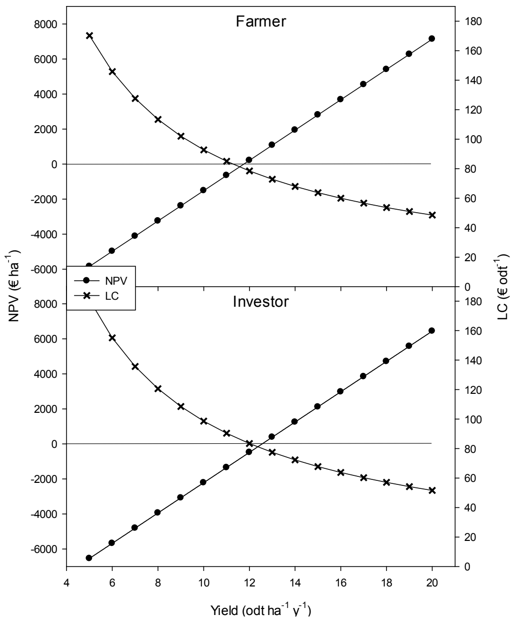

Figure 3.3 Results of the sensitivity analysis showing the impact of biomass yield on the net present value (NPV) and the levelized cost (LC) per oven-dried ton (odt) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints, farmer (top panel) and investor (bottom panel) are shown

per hectare, as a result of which the increased yield decreased the costs per unit of biomass while increasing sales revenues. The only costs of agricultural operations which could possibly increase with increasing biomass yield are the harvest costs. However, in our base case scenario, this is not the case as the harvesting was put out to subcontractors who charged a cost per hectare (see section 4.3.4). As the LC only took into account the costs of the plantation, the yield impact on this metric was moderate.

4.3.2 Land costs

In Belgium farmers can lease land at reasonable rates for a minimum period of nine years, whereas non-farmers rent land at higher prices. The rental prices for farmers are limited by law and are calculated by multiplying the (non-indexed) cadastral income of the plot with a 'tenancy coefficient'. This coefficient is determined per agricultural region by the provincial rental price commission every three years [40]. There is, however, no correlation between the soil type and the rent, as the region and the scarcity of (agricultural) land are the major variables determining the rental

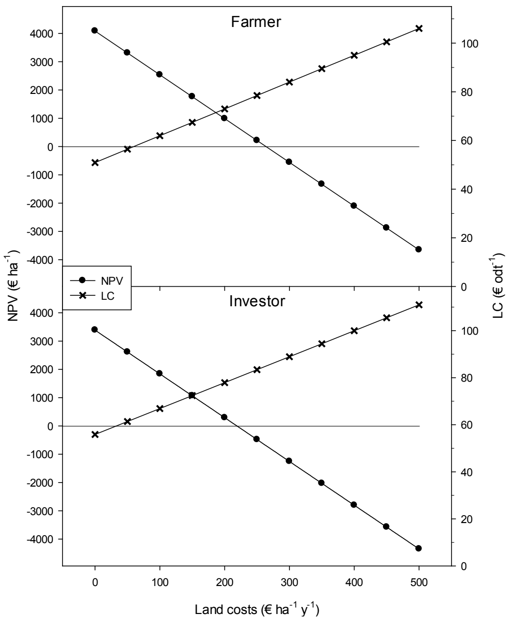

Figure 3.4 Results of the sensitivity analysis showing the impact of land costs on the net present value (NPV) and the levelized cost (LC) per oven-dried ton (odt) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints, farmer (top panel) and investor (bottom panel) are shown

price. Due to the more limited availability of suitable agricultural land in Flanders, land rent is higher in the Flemish (Northern) region as compared to the Walloon (Southern) region, averaging 273 and 202 € ha^{-1} y^{-1} respectively [41].

The land rent has a major impact on the profitability of the project. In our base case scenario we assumed a land cost of 250 € ha^{-1} y^{-1}, which is approximately the average long-term rental price for agricultural land in Belgium. An increase in this land rent by only 15 € ha^{-1} y^{-1} would render the production of SRWCs unprofitable under the base case conditions for the farmer, whereas a decrease in the base case land rent by at least 31 € ha^{-1} y^{-1} is required to make the investment in SRWCs profitable from the investor's viewpoint (Figure 3.4).

An investor, however, is not able to rent land at this low rate and is obliged to enter into a contract for a short-term rental, with much higher prices. Short-term rental prices for fertile agricultural land in Flanders start at 750 up to 1300 € ha^{-1} y^{-1}, which are roughly the annual revenues when the farmer decides to grow corn or wheat instead of renting his land [42,43]. With such high land costs, it is clear that the cultivation of SRWCs for energy purposes cannot be profitable without consider-

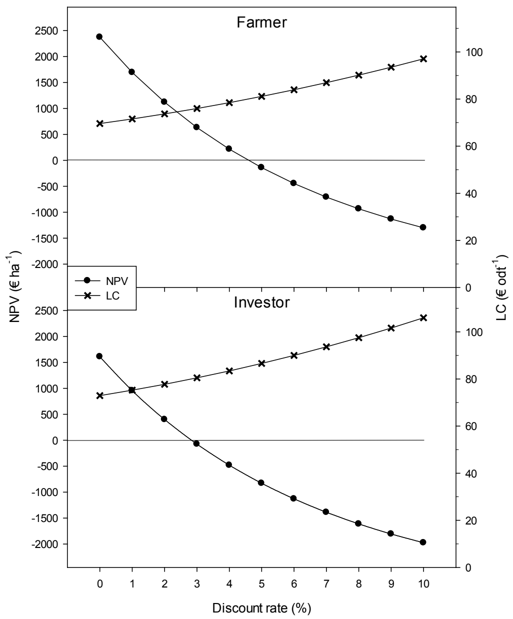

Figure 3.5 Results of the sensitivity analysis showing the impact of the discount rate on the net present value (NPV) and the levelized cost (LC) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints, farmer (top panel) and investor (bottom panel) are shown

able government incentives and/or considerable increases in the biomass sales price in Belgium from an investor's point of view. Although this is a firm conclusion of our analysis for Belgium, it cannot be extrapolated to all European countries. Recent studies [11,44] have shown that in other countries such as Poland and Spain it is economically feasible to establish and manage SRWC plantations to produce bioenergy. Furthermore, Sweden has many district heating facilities that (partly) rely on biomass from willow SRWCs of which the Enköping combined heat and power plant is a world-famous model for a successful enterprise using SRWCs [45].

4.3.3 Discount rate

As can be seen from Figure 3.5, the NPV varied inversely with the discount rate, showing a decreasing sensitivity of the NPV to the discount rate with increasing discount rates. The LC, however, was more or less linearly correlated with the discount rate and showed a lower sensitivity than the NPV. An increase in the discount rate by 1% y^{-1} increased the LC by 2.75% on average (Figure 3.5). The discount rate reflects the risk an investor or a farmer attributes to the cultivation of SRWCs, and the minimum required return on investment given this risk. This risk assessment is subjective, making the estimation of the appropriate discount rate not straightforward.

4.3.4 *Harvesting options*

Three harvesting alternatives were considered in this study, which were demonstrated at our operational POPFULL site. These harvesting machines are different in terms of the economics, the form of the harvested biomass delivered and the impact of the machines on the soil:

1) A self-propelled combined harvest-chipping machine of New Holland was used which produces chips while harvesting, decreasing the number of operations needed to produce the desired energy carrier. The major disadvantages of this machine are its weight – 13.5 Mg – and the fact that the machine is operated on tires instead of on tracks. This is not a problem as such on dry or frozen soil. The latter, however, is very unlikely to happen in the normal harvesting period, under Belgian climatic conditions. On wet soil, however, this heavy equipment causes a major compaction of the soil and forms deep ruts in the field, with a pernicious influence on the resprouting of the poplar trees.
2) A pull-type combined harvest-chipping machine from the Danish company Ny Vraa, combined with a tractor on tracks and an attached trailer specially designed for the efficient collection and unloading of biomass chips was used to harvest the willows at the POPFULL site. The advantage of this machine is its relatively low weight, both the harvester and the trailer weigh approximately 2 Mg each, in combination with tracks on both the tractor and the trailer, protecting the soil against compaction and rutting. The harvester, however, is not able to harvest trees with a diameter of more than 6 cm, which makes its usability in a poplar SRWC plantation rather limited (Henrik Bach, Ny Vraa Bioenergy I/S; personal communication).
3) A pull-type stem harvester from the Danish company Nordic Biomass, combined with a tractor on tracks was used to harvest the poplar trees at the POPFULL site. This harvester cuts the entire trees and puts the stems on the trailer with a built-in offloading system. Thanks to the tracks of both the tractor and the trailer, the impact on the soil is limited. One disadvantage of this harvesting system, however, is the necessary post-harvest chipping. When biomass chips are to be delivered, this requires additional processing of the stems to biomass chips and consequently additional costs.

An additional disadvantage of the two last mentioned Danish harvesters, as compared to the New Holland machine, is their unavailability in Belgium and its neighbouring countries. This means that the transportation costs for these Danish-based harvesters were much higher than for the New Holland harvester, which is available in Belgium (Table 3.6).

Table 3.6 Summary of the costs and working capacity of three different harvesting options applied on the POPFULL site

Harvester	Operation rate (h ha^{-1})	Operation costs (€ ha^{-1})	Transportation costs (€)	Costs * (€ odt^{-1})
Self-propelled cut-and-chipper	1.3	950	400	30.9
Tractor pulled cut-and-chipper	1.7	600	3950	23.6
Tractor pulled stem harvester	2.0	400	3950	18.0

* The costs per oven-dried ton include the harvest operation costs and the harvester's transportation costs and consider the base case scenario, based upon a planted area of 14.5 ha, a dry matter biomass yield of 12 Mg ha^{-1} y^{-1}, and a rotation length of three years.

Although common sense suggests that the operation rate (measured in h ha^{-1}) of the harvesting machines is dependent on the biomass yield as a higher yield would necessitate additional and more frequent offloading, we assumed a constant operation rate for the different machines irrespective of the assumed yield. This simplified assumption is due to the lack of reliable data concerning the correlation between yield and operation rate of the harvesting systems. The only data on the relation between the performance of the SRWC harvesting machines and the biomass yield date from 1998 and are not applicable to the newly developed and contemporary harvesters discussed in this paper [46]. Furthermore, in our analysis the harvest was subcontracted based on a rate per ha justifying a constant harvesting cost per ha, both in the farmer's and investor's scenario. This assumption implies that the harvesting cost per unit of biomass is inversely correlated with the yield, which is in line with the earlier findings of the study of Mitchell et al. [46].

Table 3.6 provides an overview of the harvest costs for the different harvesters, while Figure 3.6 depicts the NPV and the LC of the different harvesting options. The lower operation costs of the Danish companies outweighed the high transportation costs if an area of 18 ha was considered (Figure 3.6). A site of at least 10 ha is

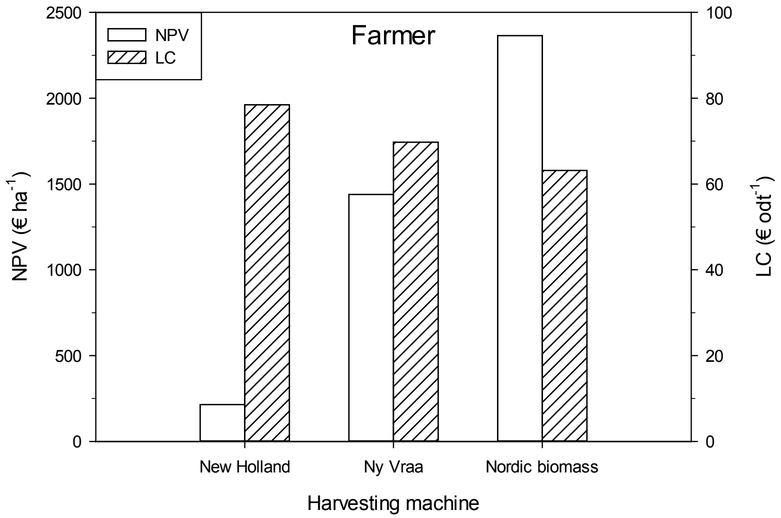

Figure 3.6 Results of the simulation runs of the POPFINUA model with different harvesting options, the diagram illustrates the impact of the harvesting strategy on the net present value (NPV) and the levelized cost (LC) per oven-dried ton (odt) from a farmer's viewpoint, the three studied harvesters include one self-propelled cut-and-chipper (New Holland), one tractor-pulled cut-and-chipper (Ny Vraa) and one tractor-pulled whole-stem harvester (Nordic biomass)

required to balance the harvesting costs of the Ny Vraa harvester with the New Holland harvester. If the land area is smaller than 10 ha, however, the Danish Ny Vraa harvester becomes more expensive than the Belgian based harvester. The Nordic Biomass stem harvester seemed the most favourable harvesting option (Figure 3.6), but could not be compared straightforwardly with the other harvesters, as post-harvest chipping operations were required to deliver the same final product (i.e. woody biomass chips). The costs of this chipping operation were 552 € ha^{-1} per harvest assuming a dry matter yield of 12 Mg ha^{-1} y^{-1} and a 50% moisture content (m.c.). If we add up this value to the harvesting costs of the stem harvester (Table 3.6), this yields 952 € ha^{-1}, which is slightly higher than the costs of Belgian based cut-and-chipper, making the stem harvester the least interesting harvesting option taking into account the higher transportation costs for this machine.

4.3.5 Transportation costs

To analyse the impact of the transportation of biomass chips on the profitability of SRWCs, we also performed a cradle-to-plant gate assessment, where the transportation to the power plant is included. In this scenario, we assumed that both the farmer and investor outsource the transportation to the power plant, as a truck and trailer are excessively expensive to be owned and used by a single farmer. Table 3.7 summarizes the assumptions and the input data for the calculation of the transportation costs of the woody biomass chips. We assume an hourly cost of 55 € h^{-1} for the transportation of the woody chips including diesel consumption and labour, in line with our experience at the POPFULL plantation and also in line with a study of NEA reporting costs of 55.66 € h^{-1} for the transportation of bulk goods [47]. Furthermore, we assume that the truck returns to the farm unloaded, incurring an extra hourly cost for the return trip. Based on the assumption in Table 3.7, we calculated that the transportation to the power plant increased the levelized cost by 15.1 € odt^{-1}, from both the investor's and the farmer's point of view. This reflects an increase in the levelized costs by 18–19% as compared to the cradle-to-farm gate assessments depicted in the base case scenario. If a cradle-to-plant gate assessment was considered, harvest and transportation costs made up almost 51% of the total discounted costs investor's scenario and more than 54% in the farmer's scenario.

Table 3.7 Summary of input data for the calculation of the transportation costs of woody biomass chips with a truck over a distance of 50 km [47,56]

	Unit	Value
Average speed	km h^{-1}	48
Hourly cost	€ h^{-1}	55
Distance	km	50
Woody chips density	kg m^{-3}	0.38
Woody chips moisture content	%	50
Maximum load capacity	Mg	27
Maximum load volume	m^3	80
Loading time	h	0.25
Unloading time	h	0.16

4.3.6 *Management activities*

As there is still a lot of discussion with regard to the optimal management of a SRWC plantation [48,49], the POPFINUA model allows the adjustment of several management parameters, i.e. rotation length, number of rotations, plantation lifetime, application of fertilizers at the establishment and/or after each harvest, number and method of herbicide treatment. For the sake of simplification, we assumed that a given operation is carried out in the same way and with the same equipment throughout the entire lifetime of the plantation. In the base case scenario, we assumed that no management (i.e. weed control or fertilization) was necessary except for initial weed control at the establishment. Obviously this is the best-case scenario, as in reality weeding and/or fertilizing after coppicing (on nutrient-poor soils) are often required to guarantee a satisfying productivity of the SRWC plantation [7]. Since SRWCs in general and poplars in particular are light-demanding crops, weed management in a SRWC plantation is especially crucial during the establishment period, and –in a lesser extent– after every harvest [7,50]. On the POPFULL plantation, intensive weed control –mechanical, chemical, and manual– was applied during the first two year after planting to decrease competition for light and nutrients. A more detailed overview of all the weed treatments that have taken place in the first two years after the establishment of the plantation was provided earlier by Broeckx et al. [20]

If we only assumed the necessity of additional mechanical weed control after each harvest, the levelized cost would increase by more than 2 € Mg^{-1} to reach 80.6 € Mg^{-1} in the farmer's scenario and the NPV would become negative, switching the investment from profitable to loss-making under the base case conditions. This analysis clearly demonstrates the financial risk involved in the cultivation of SRWCs for bioenergy, as the application of an additional mechanical weed treatment after each harvest would render the plantation loss-making under the base case conditions.

4.3.7 *Establishment grants and annual incentives*

As expected, the NPV was linearly correlated with the level of establishment grant and the level of annual incentives, but with a different sensitivity level. The NPV was 15.6 times more sensitive to an increase in the establishment grants as compared to a nominally equal increase in annual incentives, considering a plantation lifetime of 21 years. This is due to the fact that an establishment grant is only granted once,

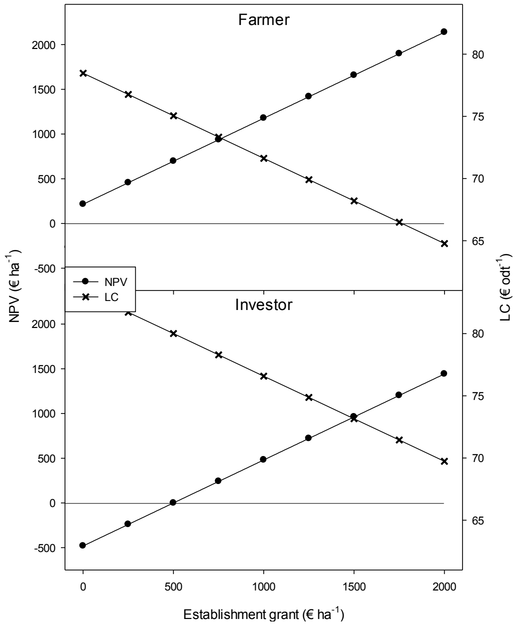

Figure 3.7 Results of the sensitivity analysis showing the impact of the establishment grant on the net present value (NPV) and the levelized cost (LC) per oven-dried ton (odt) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints, farmer (top panel) and investor (bottom panel) are shown

at the establishment of the plantation, whereas an annual incentive was defined as an annual subsidy per land area. An establishment grant of at least 500 € ha^{-1} or an annual area subsidy of at least 32 € ha^{-1} y^{-1} was required to render the investor's scenario profitable under the base case assumptions (Figures 3.7 and 3.8). Although subsidies have a major impact on the profitability of a SRWC plantation and consequently on the adoption of these energy crops by farmers (and investors), they are only justified if the life-cycle environmental performance of SRWCs for bioenergy is better than the alternatives [5,51]. As a consequence, an accurate quantification of the ecological benefits of SRWCs as compared to fossil fuels is required to work out a clear incentive program.

4.3.8 Biomass price

A farm gate price for the harvested biomass chips (50% m.c.) of at least 39.2 € Mg^{-1} and 41.7 € Mg^{-1} for the farmer and the investor respectively, was required to reach the break-even point using the base case scenario inputs (Figure 3.9). An increase in

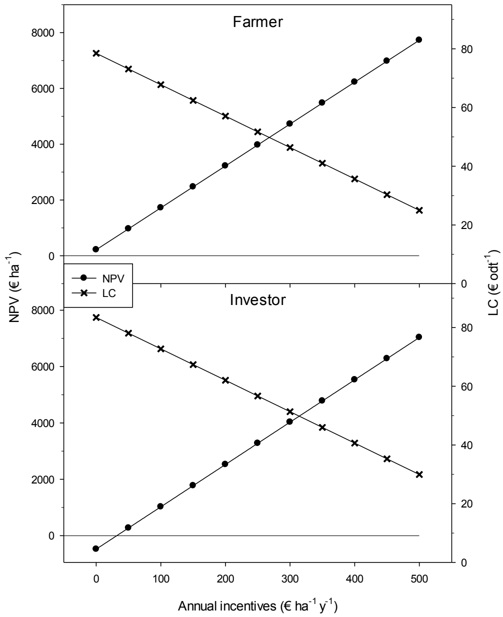

Figure 3.8 Results of the sensitivity analysis showing the impact of the annual incentives on the net present value (NPV) and the levelized cost (LC) per oven-dried ton (odt) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints, farmer (top panel) and investor (bottom panel) are shown

the biomass price by only 1 € Mg^{-1} would increase the NPV by 280 € ha^{-1} and the EAV by 20 € ha^{-1} y^{-1} (Figure 3.9). This illustrates that both the NPV and the EAV were highly sensitive to changing biomass prices. Throughout the POPFULL project, in which we have established an operational SRWC plantation, we have discovered that there is no stable national market for biomass (chips) in Belgium yet. As a consequence, wet biomass prices offered by local individual buyers fluctuated between 20 € Mg^{-1} and 30 € Mg^{-1} turning the cultivation of SRWCs into a loss-making investment (Kristof Mouton, Wood Energy bvba; personal communication). This shows that it is essential to establish a long-term stable market for biomass (chips), as a well-functioning and sufficiently valuable market is a pre-requisite for a widespread deployment of SRWCs for bioenergy [9,52,53].

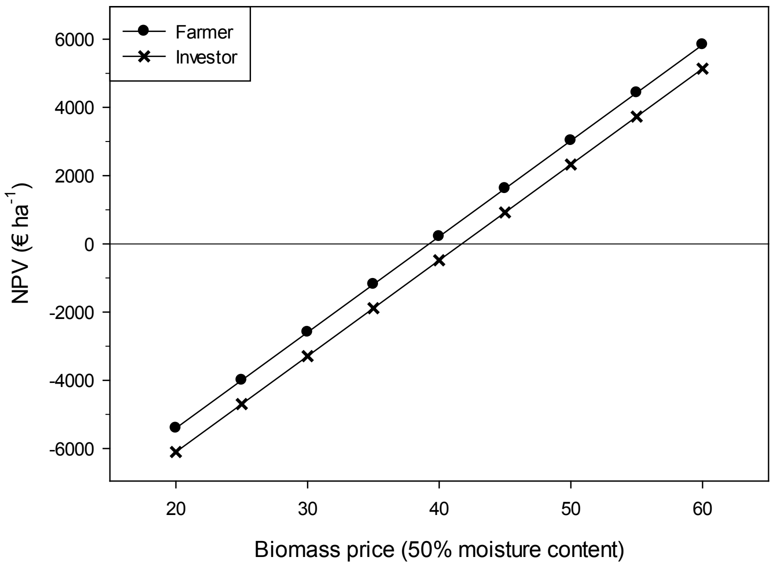

Figure 3.9 Results of the sensitivity analysis showing the impact of the biomass price on the net present value (NPV) of a short rotation coppice culture from the POPFINUA model runs, the two viewpoints (farmer and investor) are shown

5 Conclusions

This study described the influence of a number of key variables on the profitability of SRWCs in Belgium, making use of a newly developed model POPFINUA, and highlighted a number of barriers to the widespread adoption of SRWCs by Belgian farmers. In order to convince farmers to establish SRWC plantations, several conditions should be fulfilled. First of all, SRWCs should be at least as profitable (with or without government incentives) as traditional agricultural crops, such as corn [18]. Secondly, there should be a well-performing market for the produced woody biomass chips [52,53]. Thirdly, the farmer should be confident that the equipment to plant, cultivate (e.g. specially designed line cultivators for energy crops) and harvest the energy crops is available within a reasonable distance. This study shows that none of these conditions are met in Belgium at present. The cultivation of SRWCs is only financially feasible if a number of strict conditions regarding the biomass yield, biomass sales price and management activities are met and only when a farmer uses his own agricultural machines to plant and maintain the plantation. Moreover, this profit is very limited as the NPV equals 229 € ha^{-1} over the entire lifetime of 21 years for the farmer's best-case scenario. Our calculations showed that the farmer faces a very high financial risk if the crop is infested with diseases or insects or becomes overgrown with weeds, as this would require additional herbicide and/or pesticide applications switching the SRWC culture from profitable to loss-making. The inclusion of transportation by truck over a distance of 50 km increased the LC by 18–19% increasing the share of harvest and transportation costs in the total discounted costs by 9% from 45% to 54% (farmer's viewpoint) and from 42 to 51% (investor's viewpoint). Establishment grants could decrease the (initial) investment risk associated with the cultivation of SRWCs, but are only advisable if steps are taken to establish a market for the produced woody biomass chips and if the environmental benefits of SRWCs as compared to alternatives justify these subsidies. By inciting power plants to enter into long-term contracts with SRWC farmers for the delivery of woody biomass chips, the establishment of a market for biomass chips can be accelerated, as suggested by Helby et al. [52]. With regard to the life-cycle environmental impact of SRWCs, however, a thorough analysis is required as there is still a lot of uncertainty regarding the environmental costs and benefits of SRWCs (see Chapter 4).

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ENERGY AND GREENHOUSE GAS BALANCE OF BIOENERGY PRODUCTION FROM POPLAR AND WILLOW: A REVIEW

ENERGY AND GREENHOUSE GAS BALANCE OF BIOENERGY PRODUCTION FROM POPLAR AND WILLOW: A REVIEW

Abstract

Short rotation woody crops (SRWCs) such as poplar and willow are an important source of renewable energy. They can be converted into electricity and/or heat using conventional or modern biomass technologies. In recent years many studies have examined the energy and greenhouse gas (GHG) balance of bioenergy production from poplar and willow using various approaches. The outcomes of these studies have, however, generated controversy among scientists, policy makers, and the society. This paper reviews 26 studies on energy and GHG balance of bioenergy production from poplar and willow published between 1990 and 2009. The data published in the reviewed literature gave energy ratios (ER) between 13 and 79 for the cradle-to-farm gate and between 3 and 16 for cradle-to-plant assessments, while the intensity of greenhouse gas (GHG) emissions ranged from 0.6 to 10.6 g CO_2eq $MJ^{-1}_{biomass}$ and 39 to 132 g CO_2eq kWh^{-1}. These values vary substantially among the reviewed studies depending on the system boundaries and methodological assumptions. The lack of transparency hampers meaningful comparisons among studies. Although specific numerical results differ, our review revealed a general consensus on two points: SRWCs yielded 14.1–85.9 times more energy than coal (ER_{coal} ~ 0.9) per unit of fossil energy input, and GHG emissions were 9–161 times lower than those of coal (GHG_{coal} ~ 96.8 g CO_2eq MJ^{-1}_{coal}). To help to reduce the substantial variability in results, this review suggests a standardisation of the assumptions about methodological issues. Likewise, the development of a widely accepted framework toward a reliable analysis of energy in bioenergy production systems is most needed.

Keywords life cycle assessment, energy analysis, energy ratio, short rotation coppice, *Populus*, *Salix*

Published as: Njakou Djomo S., El Kasmioui O. and Ceulemans R. (2011) *Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review.* Global Change Biology – Bioenergy, 3:181–197. The author of this dissertation mainly contributed to the synthesis and review of the energy analysis studies.

1 Introduction

The progressive depletion of fossil energy sources and the growing concerns about global climate change and air quality have increased the interest in renewable energy sources that are potentially CO_2-neutral and less polluting [1]. The use of renewable energy is a way to reduce reliance on fossil fuels, to mitigate greenhouse gas (GHG) emissions, to increase energy resource diversification, and to avoid depletion risks [2]. Among renewable energies, bioenergy is considered to be relatively inexpensive and a highly promising strategy as a substitute for fossil fuels [3]. Biomass has received a renewed interest during the last 20 years and is attracting growing attention around the world as an abundant and available energy source [4,5]. The diversity of organic materials used as renewable bioenergy sources has expanded and includes agricultural and forestry residues, municipal solid and liquid wastes, agro-industrial by-products, and cultivated biomass sources. Among the cultivated biomass sources, dedicated crops and especially short-rotation woody crops (SRWCs) are the most promising [6]. SRWCs such as poplar and willow are fast-growing and high-yielding woody species which can be managed in a coppice system. This biomass can be burnt or gasified to generate electricity and/or heat in combustion or gasification plants [7]. One of the advantages of SRWCs is that they can be grown on abandoned and/or contaminated land. Thus, production does not necessarily have to compete with food crops for the most fertile soils and their management is usually less energy intensive than the one needed on food crops [8,9]. However, to be ecologically and energetically viable, the energy gain from SRWCs must outweigh the energy used for the production, transport, and conversion to bio-electricity as well as significantly reduce some impacts on the environment (e.g. GHG emissions).

A considerable number of studies has examined and compared bioenergy production systems from an energetic and environmental point of view using diverse approaches. For example, Turhollow and Perlack [10] reported on carbon dioxide (CO_2) emissions from bioenergy crops using an energy analysis (EA) approach. Mann and Spath [11] published a comprehensive life cycle assessment (LCA) study of a biomass gasification combined-cycle power system. Styles and Jones [12] used a combined LCA and economic approach to assess the environmental and economic impacts of bioenergy chains. These and other studies have advanced the understanding of the potential environmental impacts and of the energy balance of bioenergy systems. However, their

sometimes significantly different outcomes and conclusions have generated controversial views among scientists, policy makers, and the public forum [13].
This paper reviews and synthesizes published studies on environmental impacts and the energy balance of SRWCs (for the production of heat and/or electricity) where LCA, EA, or a combination of LCA and economic approaches was applied. The objectives were (i) to summarise the available information in the scientific literature about the energy and GHG balance of bioenergy production from SRWCs; (ii) to identify and investigate the mechanisms that frequently lead to conflicting results while attempting to draw coherent conclusions from the published studies, and (iii) to highlight the shortcomings in the analysis of environmental impacts.

2 Construction of literature source database

The ISI Web of Knowledge, Web of Science, and Science Direct databases were queried for original studies published in the literature between 1990 and 2009 that reported on the environmental impacts, energy balance, and/or sustainability assessment of SRWCs for the production of electricity and/or heat. The search was further extended to include grey literature such as one academic thesis, one report found by searching the archives of Wageningen University in the Netherlands, and the database of the US National Renewable Energy Laboratory. The titles and abstracts of all papers were first screened to determine their suitability; then, certain inclusion/exclusion criteria were applied to the complete articles. The bibliographies of the selected articles or reports were also examined for additional references. We attempted to contact key authors of papers that did not include the essential information needed for this review. Only published studies that reported on environmental impacts (mainly CO_2 and GHG emissions) and/or energy balance, and that presented the assessment methodology were selected. Articles reporting only on economic data, secondary review papers, papers on non-woody crops, and papers not written in English were excluded. The exclusion criteria were applied hierarchically and articles were excluded on the basis of the first exclusion criterion met. A flow chart of the selection process is provided in Figure 4.1. Key data from all included studies were then extracted and converted into same units before they were entered into the tables. The full spectrum of data categories and studies used to construct the source database of this review are presented in Table 4.1.

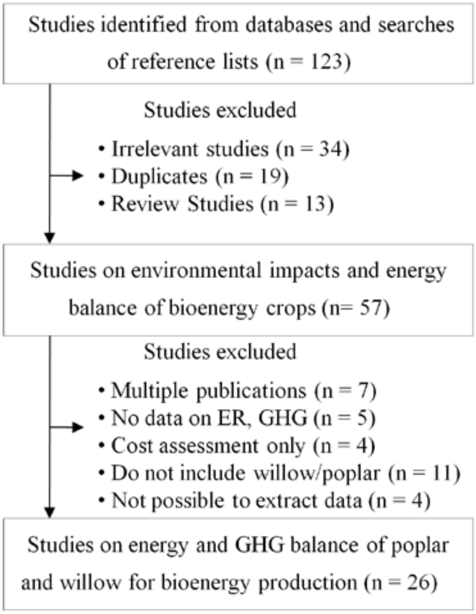

Figure 4.1 Flow chart of the construction of the literature source data base. The boxes represent the selection processes (i.e. identification of study, screening and selection). *n* represents the number of studies. The horizontal arrows represent the studies that were excluded after each stage while the vertical arrows represent the link between selection processes.

3 Types of life cycle studies

Two types of life cycle studies emerged from the reviewed literature. The first type of assessment – the so-called stand-alone assessment – describes a bioenergy production system, often in an explanatory way, in order to characterize some important environmental impacts of that bioenergy production system. In contrast, comparative life cycle studies compare the environmental impacts of bioenergy systems to other alternative energy systems.

4 Techniques and approaches used

A wide range of techniques and approaches have been used in the reviewed studies to assess the environmental effects and energy balance of SRWCs (Table 4.1). These approaches are summarized below.

Table 4.1 Overview of the methodology, energy indicators, environmental impacts, system boundaries and functional unit, reference system, types of life cycle studies and species of short rotation woody crops used in the reviewed studies.

Methodology	Energy indicators	Impacts studied	SB and FU	Conversion technology
EA	EE	CO_2	Cradle- to-plant; FU= ND	Co-combustion, combustion
EA	EE , NEY	-	Cradle-to-farm gate; FU= ND	–
EA	ER	CO_2	Cradle-to-plant; FU=ND	Co-combustion
EA	ER	CO_2	Cradle-to-farm gate; FU= ND	–
EA	ER, ERE	CO_2	Cradle-to-farm gate; FU= ND	–
EA	ER, NEY	–	Cradle-to-farm gate; FU= ND	–
EA	ER, NEY	CO_2	Cradle-to-plant; FU= 1 GJ	Co-combustion, gasification
EA	ER, NEY	CO_2	Cradle-to-farm gate; FU= ND	–
EA	NEG	A, E	Cradle-to-farm gate; FU= ND	–
EA	NER	-	Cradle-to-farm gate; FU=ND	–
EA	NEY	CO_2	Cradle-to-plant; FU= ND	Gasification
EA	PNEY	-	Cradle-to-farm gate; FU= ND	–
EA and ECA	ER	-	Cradle-to-farm gate; FU= ND	–
LCA	EE	GHG*, ODP, E, A, HT, R, SW	Cradle-to-plant; FU= 1 MJ	Gasification (with CCS)
LCA	EE, OEE	GHG*, ODP, A, E, PO, SW, R	Cradle-to-plant; FU= ND	Gasification
LCA	ER	GHG*	Cradle-to-plant; FU=1 ha	Gasification
LCA	ER	GHG*	Cradle-to-farm gate; FU= 1 GJ	–
LCA	ER	GHG**	Cradle-to-plant; FU=ND	Gasification
LCA	ER	GHG**, LU	Cradle-to-plant; FU= ND	Co-combustion
LCA	NEP	CO_2	Cradle -to-plant; FU= 1 ha	Gasification

Reference system	Types of life cycle study	SRWC species	Country	Reference
Coal power	Comparative	Poplar	Belgium	[24]
–	Stand alone	Poplar	Netherlands	[37]
Coal power	Comparative	Willow, Poplar	Sweden	[38]
–	Comparative	Poplar	Tennessee (USA)	[10]
Fossil fuel: natural gas, oil, diesel	Stand alone	Willow, Poplar	England	[23]
–	Comparative	Willow	Sweden	[25]
Coal power	Comparative	Poplar	Belgium	[22]
–	Comparative	Willow	Sweden	[26]
–	Comparative	Poplar	Germany	[28]
–	Stand alone	Poplar	Pennsylvania (USA)	[39]
Coal/natural gas power	Comparative	Willow	Sweden	[40]
–	Comparative	Willow	Germany	[29]
–	Stand alone	Poplar	Italy	[18]
Coal power	Stand alone	Poplar	Italy	[41]
Electricity mix (50% coal & 50% oil)	Comparative	Poplar	Italy	[21]
Natural gas power	Comparative	Willow	Belgium	[42]
Fossil fuel: Coal	Stand alone	Willow	Netherlands	[33]
Grid electricity	Comparative	Poplar	Pennsylvania (USA)	[43]
Peat, coal power and conventional cropland	Comparative	Willow	Ireland	[21]
Grid electricity	Stand alone	Willow	Ireland	[30]

Methodology	Energy indicators	Impacts studied	SB and FU	Conversion technology
LCA	NER	GHG**	Cradle-to-plant; FU= 1 MWh	Gasification
LCA	NER	GHG**, A, E	Cradle-to-plant; FU= 1 MWh	Gasification
LCA	NER	GHG**, A, E,	Cradle-to-plant; FU= 1 MWh	Gasification
LCA	NER	GHG**, R, ODP, HT,FWAE, MAE, TE, PO, A, E, W	Cradle-to-farm gate; FU= 3.93 TJ and 1 ha	–
LCA	NER, EE	GHG**, E, R, SW	Cradle-to-plant; FU= 1 kWh	Gasification
LCA and ECA	ER	GHG**, LU	Cradle-to-plant; FU= ND	Co-combustion

* Only CO_2 and N_2O pollutant gases were included
** CO_2, CH_4 and N_2O pollutant gases were included
A = acidification; BD= biodiversity; CCS = carbon capture and storage; E = eutrophication; EA= energy analysis, ECA= economic analysis, EE = energy efficiency; ER = energy ratio; ERE = energy requirement; EY = energy yield; FU = functional unit; FWAE = fresh water aquatic ecotoxicity; GHG = greenhouse gas; HT = human toxicity; LCA = life cycle assessment; LU= land use; MAE = marine aquatic ecotoxicity; NEB = net energy budget; NEG = net energy gain; NEP= net energy production; NER = net energy ratio; NEY = net energy yield; ND = not defined; ODP = ozone depletion potential; OEE= overall energy efficiency; PNEY = Primary net energy yield; PO = Photochemical oxidation; R = resource use; SB = system boundary SW = solid waste; TE= terrestrial ecotoxicity; W = water use.

4.1 Energy Analysis (EA)

Energy Analysis (EA) can be defined as a study that quantifies the energy consumed and carbon dioxide (CO_2) emitted in the process of making a product or providing a service [14]. It includes all processes needed to enable the manufacturing of a product, starting with the procurement of raw materials, and ending with the processing of waste. Each process of the production chain is analyzed separately. Energy and mass flow normalized per unit of product, and finally mass and energy balances are calculated for the chain as a whole. EA was one of the first techniques used in the early and mid-1990s to provide more information on the total energy used and the CO_2 emissions of SRWC systems [10].

4.2 Life Cycle Assessment (LCA)

Another widely used method is Life Cycle Assessment (LCA). The LCA methodology provides a consistent framework for the assessment of environmental aspects

Reference system	Types of life cycle study	SRWC species	Country	Reference
Grid electricity	Stand alone	Willow	New York (USA)	[44]
Grid electricity	Stand alone	Willow	New York (USA)	[34]
–	Stand alone	Willow	New York (USA)	[32]
Natural gas, Brassica	Comparative	Poplar	Spain	[20]
–	Stand alone	Poplar	Iowa (USA)	[11]
Peat and coal power	Comparative	Willow	Ireland	[12]

and potential impacts associated with a product or service [15]. It quantifies the environmental impacts resulting from the provision of a particular product or service, and it expresses them relative to a 'functional unit' (i.e., a unit that measures the usefulness of this system) [16]. Its principle may be summarized by the 'cradle-to-grave' approach, according to which all flows of matter and energy into and out of the production system are inventoried [15]. The specificity of LCA is that it avoids shifting the impacts from one area of protection to another. LCA is a compilation of several interrelated components: goal definition and scope, inventory analysis, impact assessment, and interpretation [17]. Unlike EA, LCA studies include a wider range of environmental impacts (e.g., acidification, eutrophication, ozone depletion, human toxicity, ecotoxicity) in addition to energy used and CO_2 or greenhouse gas (GHG) emissions.

4.3 Combined or integrated approaches

The combined energetic-economic analysis [18] and combined LCA-economic analysis [12] are other approaches used to assess or to compare the environmental, energetic, and economic sustainability of bioenergy production systems or chains. These approaches integrate costs and LCA information into a consistent framework model. They differ from the two previously mentioned methods as they include -in addition to energy and environmental impacts- producer and consumer profitability, the financial valuation of externalities (typically CO_2 avoidance benefits) associated with bioenergy crop production, transport, and conversion, as well as impacts so far insufficiently addressed.

5 System Boundaries (SB) and Functional Unit (FU)

The system boundary (SB) is the interface between the product (e.g., bioenergy system) and the environment (i.e., other product systems). It delineates which unit processes are included within the LCA. System boundaries vary among studies in the reviewed literature and one of the most striking features among studies is the number of stages in the life cycle of bioenergy systems that are assessed and compared against the lifetime energy output of the system. Most of the cradle-to-farm gate assessments include the acquisition of raw materials, cultivation and harvesting, and sometimes transport and storage at the farm gate or intermediary storage place (Table 4.1). The cradle-to-plant studies include the transport of biomass to the power plant, biomass fuel preparation, conversion to electricity, and treatment of waste in addition to the stages listed in the cradle-to-farm gate studies. The spatial and temporal boundaries also differ among the reviewed studies.

The functional unit (FU) describes the primary function fulfilled by a product system, and indicates how much of this function is to be considered in the LCA study [16]. The FU is the reference unit that forms the basis for comparisons between different systems. The FU in the reviewed studies, depending of the goal and scope of the studies, is expressed in terms of per unit land area (1 ha), per unit energy content of biomass (1 GJ), or in terms of per unit usable energy output (1 GJ or 1 kWh electricity).

6 Conversion technologies

A number of biomass conversion technologies have been reported in the literature for converting SRWCs to usable energy (i.e., electricity, heat, or both electricity and heat). These conversion technologies can be grouped into two types: (i) direct combustion technologies such as conventional combustion and co-combustion and (ii) indirect combustion technology such as gasification (Table 4.1). In the direct combustion system, biomass from SRWCs is directly burnt to produce high-pressure steam to generate electricity, while in the co-combustion system, the biomass is co-combusted with coal as a small proportion of input fuel for the generation of electricity or heat. Gasification processes convert biomass from SRWCs into combustible gases that ideally contain the energy originally present in the biomass. These gases are then burnt to produce electricity and/or heat.

7 Reference systems

System analysis is possible by comparing the bioenergy system with a targeted reference system [19], which in most reviewed studies is limited to a fossil fuel system. Five types of reference systems -fossil fuel, biofeedstock *(Brassica carinata)*, fossil power plant, grid electricity, and previous land use- have been used in the reviewed studies (see Table 4.1). In the cradle-to-farm gate assessment, harvested biomass from SRWCs is compared (on the energy content of the fuels) to fossil fuels such as coal and natural gas. The land area (1 ha) is also used in the study of Gasol *et al.* [20] to compare SRWCs with other bioenergy systems such as the *Brassica carinata* cropping system in addition to the energy content of the biofeedstock. This comparison is expressed in terms of MJ ha^{-1}. In one study [21], the reference system also included the previous land use expressed in ha yr^{-1} in order to determine the carbon emissions from the change of land use.
In the cradle-to-plant assessment the bio-power system is compared to conventional power systems such as a coal power plant, a natural gas power plant, a coal or natural gas combined heat and power (CHP) plant, or to regional grid mix electricity.

8 Environmental impacts

One of the primary incentives for producing bioenergy is its capacity to reduce greenhouse gas (GHG) emissions as compared to fossil energy. However, as conventional energy production systems, bioenergy production systems cause environmental impacts. Environmental impacts are the consequences of the physical interactions between the studied system and the environment. In practice, all environmental impacts can be classified in several categories of environmental problems. These impact categories range from global impacts such as climate change (GHG balance), regional impacts such as acidification, to local impacts such as eutrophication, or ecotoxicity impacts. With regard to bioenergy from SRWCs, the most common environmental impacts reported in the reviewed studies are GHG emissions, and to a lesser extent acidification, eutrophication, solid wastes, and resource use (Table 4.1). These impacts depend on various factors such as the SRWC cultivation practice, land management, location, and downstream processing and distribution routes.

9 Energy performance indicators

In the reviewed studies over the period from 1990 to 2009, ten energy metrics were used to quantify the net renewable energy yield over the life cycle of SRWCs (Table 4.1). Often, these energy indicators are defined differently but have the same meaning. These energy indicators are summarized below.

9.1 Energy Efficiency (EE)

The energy efficiency [11] or overall energy efficiency [21] is defined as the ratio of the usable energy (e.g., electricity) produced to the energy contained in the biomass feedstock. Usually expressed as a percentage, the EE gives the fraction of energy in the biofeedstock that is converted to the final energy product (i.e., electricity). A higher EE indicates a more efficient conversion process.

9.2 Life Cycle Efficiency (LCE)

The EE as defined above does not include the energy consumed by the upstream processes. With reference to life cycle assessment, an appropriate energy metric found in the reviewed studies for system efficiency is the LCE. The LCE [11] or overall system efficiency [21] is defined as the ratio of the difference between the usable energy produced and the energy consumed by the upstream processes to the energy contained in the biomass feedstock. The LCE can be negative, and a negative LCE indicates the overall system energy deficit. The LCE and EE were found mostly in studies using the cradle-to-plant approach.

9.3 Energy Ratio (ER)

Studies that used the cradle-to-farm gate approach [10,22,23] defined the energy ratio (ER) as the ratio of the energy contained in biomass to the energy inputs to produce the biomass feedstock. In the cradle-to-plant studies, the net energy ratio [11,24] was defined as the total usable energy (i.e., electricity, heat, or both electricity and heat) produced by the system divided by the total energy input to drive the system. Typically, only fossil energy inputs are included in this ratio, while the renewable inputs, including biomass feedstock itself, are not included. This energy metric reveals the influence of the inputs expressed in energy units to obtain either the biofeedstock (i.e., in the cradle-to-farm gate case) or the usable energy product (i.e., in the cradle-to-plant case). The ER is dimensionless and it illustrates how much energy is produced for each unit of fossil fuel energy consumed. An ER less than 1 implies that the energy input is higher than the produced energy output.

9.4 Energy Requirement (ERE)

The energy requirement [23] is the ratio between the energy inputs to produce the biomass feedstock versus the energy contained in the biomass. It is thus the inverse of the energy ratio. The ERE of a bioenergy production system is less than 1 if the system produces more energy than it consumes [23].

9.5 Net Energy Yield (NEY)

The net energy yield [25,26] or net energy budget [27], also referred as net energy gain [28] or primary net energy yield [29] or net energy production [30] is the difference between the gross energy output produced (i.e., the energy content of the biomass at the farm gate) by the bioenergy system and the total energy required to obtain it (i.e., the fossil energy input). In bioenergy processes this energy metric is normally related to the unit of production (e.g., 1 ha). The NEY combines productivity and energy efficiency into one value. A smaller NEY means that the bioenergy system requires more land to produce the same amount net of energy, when the surface area is used as the unit of production.

9.6 Energy Use Efficiency (EUE)

Finally, another energy indicator used in the cradle-to-farm gate approach to assess the direct and indirect energy required to produce a unit of energy is the energy use efficiency. The EUE [29] is defined as the ratio of the primary net energy yield (the difference between the primary energy yield and the energy consumption) to the energy consumption. As in the case of ER, an EUE greater than unity indicates that the system produces more unit energy than is consumed by the biomass production processes.

10 General characterization of the reviewed studies

The majority (19 of 26) of the reviewed studies were undertaken in Europe, and the remainder in the USA. Besides two studies that examined both poplar *(Populus)* and willow *(Salix)*, a similar amount of studies examined either poplar or willow. Fifteen of the 26 studies quantified and compared the energetic and ecological performance of SRWCs with fossil fuels or other bioenergy systems, while 11 of the 26 evaluated the performance of SRWCs alone without comparisons. Of the reviewed studies the LCA and EA approaches were equally used (46% each), whereas the combined approach was used less frequently (8%). Sixteen studies made the cradle-to-plant assessment and the rest were cradle-to-farm gate assessments. Some of the cradle-to-plant assessments (10 studies) also presented the results of the cradle-to-farm gate stages. Thus, data for 20 cradle-to-farm gate studies could be extracted and analyzed from the reviewed studies (Table 4.2). Of the cradle-to-plant assessments, gasification appeared to be the most applied conversion technology among the main conversion technologies reported in the reviewed studies to convert biomass to electricity and/or heat.

More than half (16) of the reviewed studies did not explicitly refer to the functional unit, but instead normalized the mass and energy flows per unit of product energy output. Nevertheless, the resulting unit reflects the concept correctly. Among the studies that clearly defined the FU, the land area (1 ha) or energy unit (1 GJ, 1 kWh) were chosen as the functional unit. All studies quantified the energetic performance of SRWCs, although there were differences in the energy indicators used in the assessments. More than three-quarters of all studies provided information on the CO_2 or GHG emissions of SRWCs. However, in many cases only one or a few pollutant gases contributing to this impact category were included in the assessment. About a quarter of the studies did not assess any environmental impacts. Other important environmental impacts (non-GHG impacts) were less studied. For example six studies included acidification, eutrophication, and/or resource use impacts. Only three of the reviewed studies included ozone depletion, photochemical oxidation and solid waste impacts. Land use and water use were reported the least (i.e., in only two studies).

11 Energy balance versus environmental impacts

This section analyses and compares the range of results presented in the reviewed studies. Due to the limited data extracted from the studies focusing on the cradle-to-plant assessment, the focus of the analysis and comparison is restricted mainly to the cradle-to-farm gate assessment. Given the small number of studies presenting results on impact category indicators other than GHG emissions, they were not analyzed in detail. Table 4.2 provides the detailed technical results on the energy indicators and on the GHG emissions. The main data on SRWCs included yield, the life span, total biomass production, ER and CO_2 or GHG emissions. Yields ranged from 4.2 to 16.8 ton ha^{-1} yr^{-1} and the life span varied from 8 to 35 years (Table 4.2). The variation in yield can be explained by the agronomic practices which vary with intensity of production, the edaphic and climatic conditions. The mean harvestable yield was 11.5 ton ha^{-1} yr^{-1} and the median 11.7 ton ha^{-1} yr^{-1}. With regard to SRWCs, the mean and median yields of poplar and willow were comparable (Figure 4.2).
The ER values ranged from 13 to 79 for the cradle-to-farm gate and from 3 to 16 for the cradle-to-plant assessments, respectively. The ER value was lower if the final output was quantified in terms of electricity generated rather than as the energy content of the produced biomass from SRWCs. There was no exception to this finding. This result is indeed consistent with the fact that expanding the boundary beyond the farm gate to include conversion to electricity should always result in a lower ER. Assumptions about energy use in biomass production and the efficiency of biomass conversion to electricity had large effects on the cradle-to-plant ER.

Table 4.2 Energy ratios, CO_2 and GHG emissions, biomass yield and species of short rotation woody crops reported in the reviewed studies.

Energy ratio		CO_2 and GHG emissions	
Cradle-to-farm gate	Cradle-to-plant	Cradle-to-farm gate	Cradle-to-plant
13	NA	NA	NA
15	NA	NA	NA
16	NA	1.3 kg C $GJ^{-1}_{biomass}$	NA
16	4	10.6 g CO_2eq $MJ^{-1}_{biomass}$	132 g CO_2eq kWh^{-1}
19	3	NA	NA
20	NA	3.8 kg CO_2eq $GJ^{-1}_{biomass}$	NA
21	NA	0.7 kg C $GJ^{-1}_{biomass}$	NA
22	NA	1.1 kg C $GJ^{-1}_{biomass}$	NA
22–26	NA	1.7-1.9 kg C $GJ^{-1}_{biomass}$	2.9 kg C GJ^{-1}
23	NA	NA	NA
26	NA	NA	NA
29	NA	1.3 g C $MJ^{-1}_{biomass}$	NA
32	NA	9.8 g CO_2eq $MJ^{-1}_{biomass}$	NA
38	8*	2.1 g CO_2 $MJ^{-1}_{biomass}$	58 kg CO_2 GJ^{-1}*
48	NA	0.5 kg C $GJ^{-1}_{biomass}$	NA
50	NA	1.9 - 2.0 g CO_2eq $MJ^{-1}_{biomass}$	NA
50	NA	NA	NA
55	11	0.7 g CO_2eq $MJ^{-1}_{biomass}$	NA
55	13	0.7 g CO_2eq $MJ^{-1}_{biomass}$	39 g CO_2eq kWh^{-1}
55	16	0.6 g CO_2eq $MJ^{-1}_{biomass}$	46 g CO_2eq kWh^{-1}
79	NA	NA	NA

* Values obtained after allocation of impacts to electricity production only
GHG = greenhouse gases; NA = not assessed

Biomass				
Yield ($t\ ha^{-1} yr^{-1}$)	Life span (yr)	Total harvestable biomass ($t\ ha^{-1}$)	SRWC species	Reference
10	8	76	Poplar	[18]
16	15	NA	Poplar	[39]
11.3	18	252	Poplar	[10]
8.8	23	202	Willow	[21]
4.2	20	74	Poplar	[24]
15.6	15	212	Willow	[33]
9	24	216	Willow	[26]
16.8	NA	NA	Willow	[38]
10–15	23	235–345	Poplar	[22]
5	20	100	Poplar	[37]
9	NA	NA	Willow	[40]
8–12	16	128–168	Willow	[23]
10	25	250	Willow	[42]
10	NA	NA	Willow	[30]
7	30	210	Poplar	[43]
13.5	17	216	Poplar	[20]
6.9	20	138	Poplar	[28]
13.6	23	214.4	Willow	[32]
13.6	23	214.4	Willow	[44]
13.4	35	469	Poplar	[11]
15.2	16	235	Willow	[29]

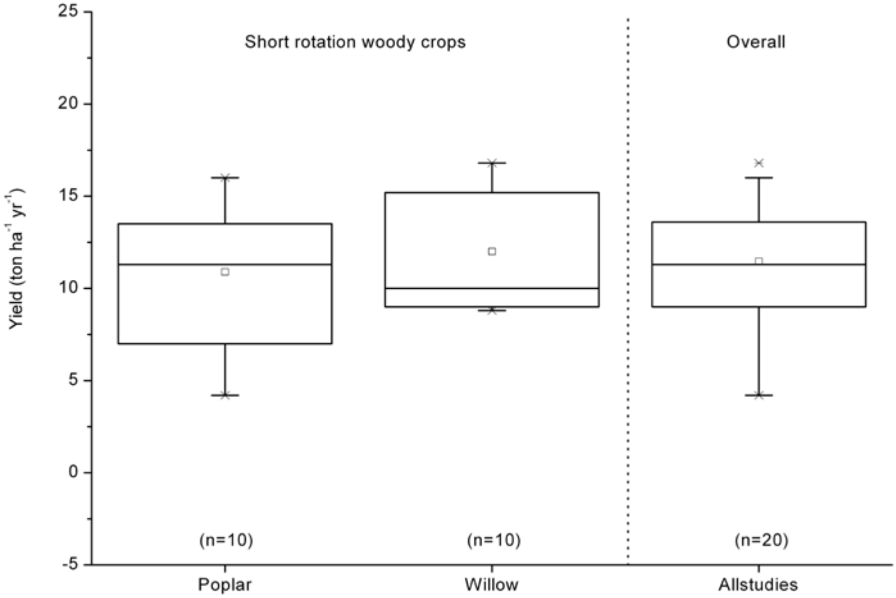

Figure 4.2 Comparison of the yield of the two tree species of short-rotation woody crops (SRWCs) analyzed in this study. The boxes represent the interquartile range (IQR, i.e. the 25th to the 75th percentile), the horizontal lines within the boxes represent the medians, the small squares within the boxes represent the means, the vertical lines drawn from the edges of the IQR boxes represent the whiskers (i.e. the largest and smallest values within 1.5 IQR), the horizontal lines on the whiskers represent the outliers (i.e. values which are within 1.5 and 3 IQR lengths from the upper and lower boundaries). The number *n* in this figure represents the number of studies included in the analysis.

The highest cradle-to-plant ER value (i.e., 16) was for the gasification plant that had an electrical conversion efficiency of 37.2%. The direct biomass combustion technology had a much lower efficiency (η = 27.7%) as well as ER value (9.9) than the gasification technology. Despite its high electrical efficiency (η = 37.5%), biomass co-combustion technology had a low ER value (i.e., 4). This was mainly due to the relatively high energy requirements for biomass production that were (coincidentally) assumed in the studies that used co-combustion as a conversion technology. The mean and the median ER values of the reviewed studies (cradle-to-farm gate) were 32.5 and 24.5, respectively (Figure 4.3). The variation in the ER values can be attributed to differences in yield, to the types of fertilizer used and their application rates, and to major differences in the method of harvesting.

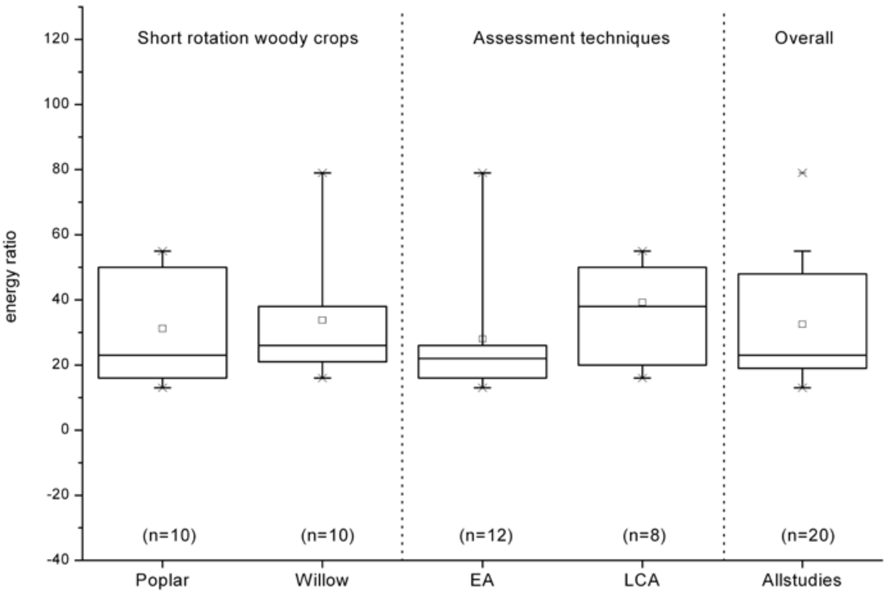

Figure 4.3 Cradle-to-farm gate energy ratios (ER) of the reviewed bioenergy systems classified into types of short-rotation woody crops (SRWCs), assessment techniques, and overall studies. Twenty studies which presented data on ER were analyzed in this graph. The whiskers boxes of this figure are explained in Figure 4.2.

Table 4.3 presents the processes that contributed to energy input in the investigated bioenergy system of each of the reviewed studies. The components (i.e., processes) within the investigated bioenergy systems in the reviewed studies vary considerably. This variability illustrates the diversity of the systems in which SRWCs can be and are grown. The total energy input ranged from 46.3 GJ ha^{-1} to 247.7 GJ ha^{-1}, while the energy output ranged from 1418 GJ ha^{-1} to 6930 GJ ha^{-1} depending on the life span. The energy input was higher in fertilized bioenergy systems (i.e., intensive) than in unfertilized (i.e., extensive) bioenergy systems. The comparison of different energy consuming processes revealed that harvesting and fertilization (i.e., fertilizer production plus their application) accounted for the majority of the energy input to the bioenergy system. Harvesting accounted for 8% to 76% of the energy input in the bioenergy production across the reviewed studies followed by fertilization, which

Table 4.3 Cradle-to-farm gate energy input and output, contribution of energy consuming processes (included in or excluded from the system boundaries), and species of short rotation crops reported in the reviewed studies.

Cradle-to-farm gate energy (GJ ha^{-1})		Process contribution in (%)				
Total input	Total output	Capital equipment	Cuttings production	Transport	Tillage/ Planting	Herbicide/ weeding
46.3	1759.4	-	3.3	-	2.6	2.2
49.5	3933.2	-	-	-	7.5	5.3
52.4	2622.1	-	na	na	na	na
75.2	1418.0	-	na	na	na	na
79.0	1800.0	-	-	-	8.9	5.1
84.2	4104.2	5.2	-	2.5	19.3	4.5
84.4	4053.2	na	na	na	na	na
98.3	5434.9	3	9	2	3.1	4.3
105.0	3006.2	-	-	3	8	4
113.6	1504.0	-	-	-	8.3	7.6
115.0	3024.0	-	-	na	na	na
123.7	1860.5	-	-	-	7.4	2.5
126.2	6930.3	1.8	-	-	-	-
140.9	4509.1	-	1.9	11.9	2.2	1.8
155.0	3225.3	-	3.2	9.8	2.3	2.1
184.9	4198.0	-	-	-	3.2	5.2
202.0	4320.0	-	3.5	15.3	4.2	1
211.7	4761.2	2.1	3.4	-	4.3	-
234.4	3663.4	3.7	3.2	-	2.2	2
247.7	4027.3	1.2	-	10.4	8	3

The sum of all contributions does not always give 100%.
- = The process is not included in the system boundary, na = not assessed.
‡ Irrigation is included in the system boundary but no value for the breakdown is available.
†This value includes the contribution of all farming processes, except fertilization.

Fertilization	Irrigation	Fencing	Harvest/ Chipping	Storage/ drying	Grubbing up	SRWC species	Reference
40.6	-	14.6	35.2	-	1.6	Willow	[30]
36.1	-	-	42.6	-	8.5	Willow	[29]
na	na	na	na	na	na	Poplar	[28]
na	na	na	na	na	na	Poplar	[24]
10.1	-	-	75.9	-	-	Poplar	[37]
35.6	*	-	32.9	-	-	Poplar	[20]
na	na	na	na	na	na	Poplar	[43]
39	-	-	38.4	-	1.2	Willow	[32]
-	-	13	30	40	2	Willow	[23]
63.7	-	-	18.9	-	1.4	Poplar	[18]
na	-	-	-	-	-	Willow	[40]
14.2	-	-	75.8	-	-	Poplar	[39]
15.4	-	-	82†	-	-	Poplar	[11]
48.3	-	-	26.6	-	7.3	Willow	[42]
47.5	-	-	30.8	-	4.3	Willow	[33]
37.5	-	-	51.4	-	2.2	Poplar	[22]
51.1	-	-	24.9	-	-	Willow	[26]
58.7	-	-	31.3	-	-	Willow	[38]
55.8	-	11.7	8	8.1	1	Willow	[21]
24.2	-	-	53.1	-	-	Poplar	[10]

accounted for between 10% and 64% of the energy input, depending on the growing conditions. Fertilizer production constituted the major part (~90%) of energy consumed in the fertilization step. Herbicide treatment and weeding contributed between 1% and 8% of the total energy input of the bioenergy systems in the reviewed studies. Other mechanical operations, such as tillage and planting or the removal of stumps (grubbing up), required less energy than harvesting and fertilization and mainly concerned the planting of SRWCs. They involved energy inputs ranging from 2% to 19% for tillage and planting, and from 1% to 9% for the removal of stumps. The contribution from the production of cuttings ranged from 2% to 9% across the reviewed studies. Transport is also an important component in the energy consumption of bioenergy systems as its contribution ranged from 2% to 15%. In general, harvesting and fertilization processes were the major contributor to energy input in the reviewed studies. However, in some studies processes such as active drying and fencing had far-reaching impacts on the energy input as well as the ER. For example, in the study of Matthews [23], the contribution of active drying and fencing totaled 53% (Table 4.3). When these processes (i.e., active drying and fencing) were excluded from the system boundary of the analysis, the resulting ER was 60 [23]. Similarly, the ER reported by Goglio and Owende [30] and that reported by Styles and Jones [21] respectively increase from 38 to 45 and from 16 to19 if the contribution of fencing was excluded from their analyses. It is worth mentioning that active drying of SRWCs depends on the end use. Drying may not be required if the produced biomass is dried on farm; it could be performed at the conversion site (using waste heat) or not be performed if the conversion system can use wet chips. With regard to the techniques used, the cradle-to-farm gate ER values ranged from 16 to 55 for LCA and from 13 to 79 for EA, respectively. The EA technique determined a lower mean (28) and median (22.5) ER compared to LCA. The ER interquartile range (IQR) is lower for the EA technique than for LCA, but overlaps with it (Figure 4.3). Results from the two techniques varied because of the difference in the types and sources of data, assumptions about farm inputs, and the computation methods. Many LCA studies combine primary data and sometimes secondary data available in the life cycle inventory databases, while EA uses data from producers. EA uses simple computational tools (e.g., Microsoft Excel spreadsheets), whereas simple as well as complex dedicated tools (e.g., Simapro, Gabi) are used in LCA to model the bioenergy system.

With regard to the type of species of the SRWCs, the ER values ranged from 16 to 79 for willow and from 13 to 55 for poplar, respectively. The mean and median ER values for willow and poplar were found to be nearly identical (i.e., 33.8 and 27.5, respectively, for willow versus 31.2 and 23, respectively, for poplar (Figure 4.3). Their ER IQR and whisker also overlap. Thus, one can conclude that, on average, willow and poplar have very similar ER values.

In general and regardless of the techniques used, the ER values reported in the reviewed studies for both willow and poplar indicate a high ER (i.e., there is a high energy return). On the basis of fossil energy inputs, SRWCs improve the effective use of this finite energy source. Therefore, the cultivation of SRWCs for bioenergy production can be considered beneficial from an energy perspective.

The intensities of GHG emissions ranged from 0.6 g to 10.6 g CO_2eq $MJ^{-1}_{biomass}$ for the cradle-to-farm gate and from 39 g to 132 g CO_2eq kWh^{-1} electricity for the cradle-to-plant assessment. The intensity of GHG emissions was larger when the final output was given as electricity generated rather than as the energy content of the biomass from SRWCs. This difference is simply due to the efficiency of biomass conversion to electricity. The gasification technology had the lowest intensities of GHG emissions (39 g CO_2eq kWh^{-1}) due to its high efficiency ($\eta = 37.2\%$), followed by the direct combustion technology (52.3 g CO_2eq kWh^{-1}). Co-combustion technology ($\eta = 37.5\%$) had the largest GHG emission intensities. This high value of GHG emission intensities for the co-combustion technology was due to the relatively high GHG emissions in biomass production that were (coincidentally) assumed in the co-firing studies, and to the up- and downstream GHG emissions from coal.

The wide range of cradle-to-farm gate CO_2 and GHG emissions observed among the reviewed studies can be attributed to the agrochemical input (mainly fertilizer), assumptions about N_2O linked to fertilizer input, the carbon sequestration process (soil carbon and carbon pools below ground), and the N_2O and CH_4 associated with the decomposition of leaves and litter (Table 4.4). The types of fertilizer used differed among the reviewed studies. Ammonium-based fertilizer (e.g., ammonium sulfate), nitrate-based fertilizer (e.g., ammonia), and urea are some types of fertilizer used in the reviewed studies. Nitrogen fertilizer requirements varied from 40 kg to 138 kg N ha^{-1} while the emission factors associated to fertilizer production varied substantially depending on the production process.

Many reviewed studies overlooked N_2O emissions from fertilizer application; those

Table 4.4 Cradle-to-farm gate CO_2 and greenhouse gas (GHG) emissions, contribution of sources and sink of GHG emissions (included in or excluded from the system boundaries), coppice cycle, and species of short rotation woody crops GHG reported in the reviewed studies.

Cradle-to-farm gate CO_2 and GHG emissions		Sources and sink of greenhouse gas emissions (%)				
Net total	Total without sequestration	Management	Agricultural input	Fertilisation (N_2O)	Decomposition	Carbon sequestration
0.6 g CO_2eq $MJ^{-1}_{biomass}$	-	84.6	15.4	-	-	-
0.7 g CO_2eq $MJ^{-1}_{biomass}$	3.2 g CO_2eq $MJ^{-1}_{biomass}$	17.8 (86)	18.9 (91)	22.3 (107)	40.9 (197)	(- 381)
1.7 g CO_2eq $MJ^{-1}_{biomass}$	na	na	na	na	na	na
1.9 g CO_2eq $MJ^{-1}_{biomass}$	-	49	39.4	11.6	-	-
2.1 g CO_2 $MJ^{-1}_{biomass}$	-	67.6	32.4	-	-	-
3.1 g CO_2 $MJ^{-1}_{biomass}$	-	50	50	-	-	-
3.8 g CO_2eq $MJ^{-1}_{biomass}$	8.4 g CO_2eq $MJ^{-1}_{biomass}$	24.9 (55)	19.2 (42)	42.3 (95)	13.6 (30)	(- 123)
3.9 g CO_2 $MJ^{-1}_{biomass}$	-	44.8	55.3	-	-	-
4.8 g CO_2 $MJ^{-1}_{biomass}$	-	na	na	-	-	-
4.8 g CO_2 $MJ^{-1}_{biomass}$	-	72.8	27.2	-	-	-
6.2- 6.9 g CO_2 $MJ^{-1}_{biomass}$	-	67	33	-	-	-
9.8 g CO_2eq $MJ^{-1}_{biomass}$	-	9.7	13.6	76.8	-	-
10.6 g CO_2eq $MJ^{-1}_{biomass}$	-	7.7	47.8	23.1	-	-

The values between parentheses represent the contribution to GHG emissions when carbon sequestration is considered.
na = not assessed

that included N_2O used the IPCC methodology for direct and indirect N_2O emissions estimation [31]. Two studies included the decomposition of leaves and litter in their assessments and reported GHG emissions values ranging from 1.1 g to 1.3 g CO_2eq $MJ^{-1}_{biomass}$ [32,33].

Few reviewed studies included the carbon sequestration process (soil carbon and carbon pools below ground) in their analyses. In the small number of reviewed studies in which values are incorporated, data ranged from -2.7g to -4.7 g CO_2eq $MJ^{-1}_{biomass}$ (Table 4.4). However, it is important to note that the sequestration of carbon in soil is site-specific and depends on factors such as existing soil carbon levels, climate, soil characteristics, and management practices [34]. Generally, SRWCs would be expected to significantly increase soil carbon in arable soils, but not in grassland

Biomass		
Coppice cycle	SRWC species	Reference
7	Poplar	[11]
3	Willow	[32]
10	Poplar	[43]
5	Poplar	[20]
3	Willow	[30]
na	Willow	[26]
2	Willow	[33]
6	Willow	[38]
3	Willow	[23]
na	Poplar	[10]
na	Poplar	[22]
3	Willow	[42]
3	Willow	[21]

soils. It can therefore be argued that accounting for carbon sequestration is not always relevant, and depends on system boundaries and displacement assumptions (even when planted on tillage land SRWCs may ultimately displace grassland if arable production shifts onto grassland).

The intensities of CO_2 emissions ranged from 2.1 g to 6.2 g CO_2 $MJ^{-1}_{biomass}$ for EA, the mean CO_2 emission intensities was 4.7 g CO_2 $MJ^{-1}_{biomass}$. EA studies solely focused on CO_2 emissions from fuel combustion and CO_2 emissions from farm material production and overlooked the carbon sequestration process as well as non-CO_2 GHG emissions such as N_2O from fertilization (Figure 4.4a). The mean and median GHG emissions intensities were 4.1 g and 1.9 g CO_2eq $MJ^{-1}_{biomass}$ for the LCA technique, respectively (Figure 4.4b).

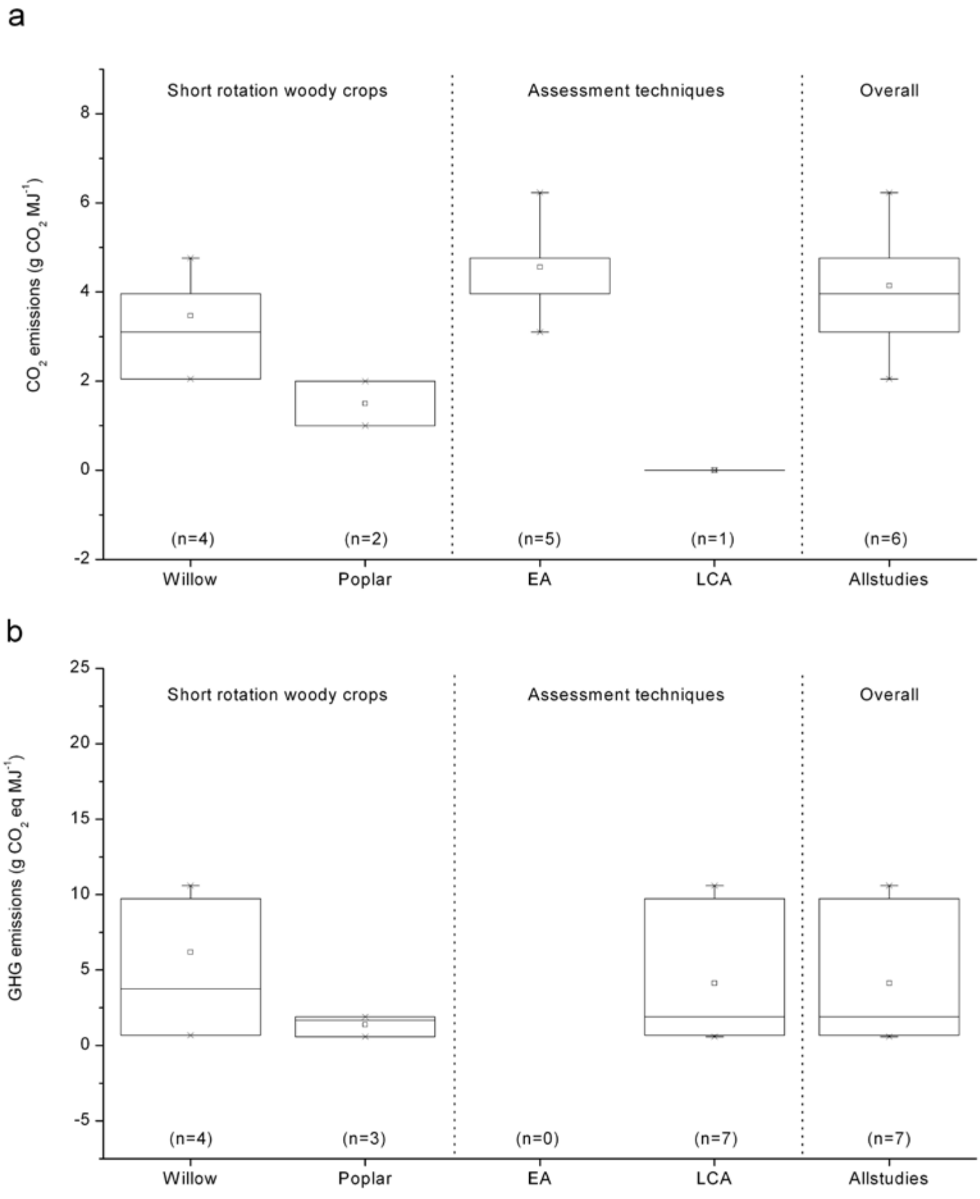

Figure 4.4 Cradle-to-farm gate carbon dioxide (CO_2) emissions (a), greenhouse gas (GHG) emissions (b) of the reviewed bioenergy systems classified into types of short rotation woody crops, assessment techniques, and overall studies. Thirteen studies which presented data on CO2 and GHG emissions were analyzed in this graph. The whiskers boxes of this figure are explained in Figure 4.2.

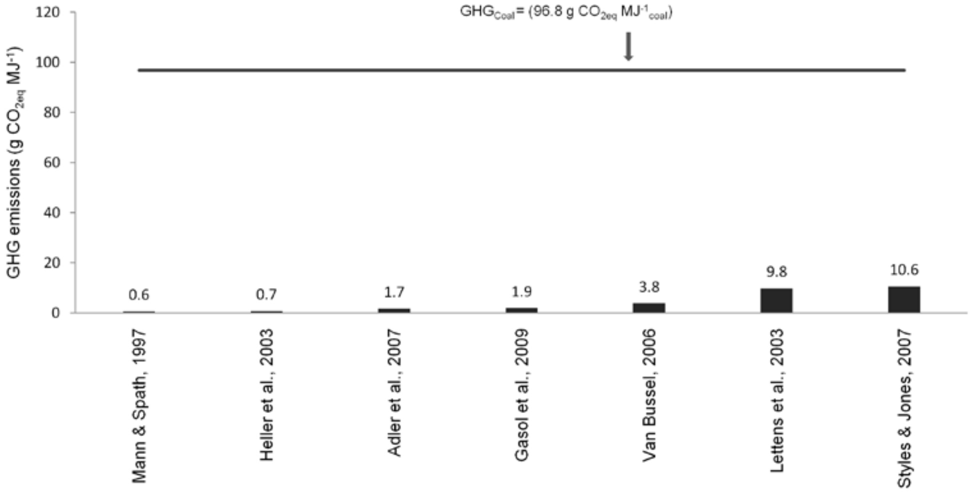

Figure 4.5 Cradle-to-farm gate greenhouse gas (GHG) emissions for short rotation woody crops as compared to coal. The comparison is based on GHG emissions MJ^{-1} energy content of biomass and coal from seven studies. The bars represent the values of GHG emissions of SRWCs. The horizontal line above indicates the value of the reference system (i.e. coal).

With regard to the tree species in SRWCs, the intensities of CO_2 for willow ranged from 2.1 g to 4.8 g CO_2 $MJ^{-1}_{biomass}$, while for poplar the range was 4.8 g to 6.2 g CO_2 $MJ^{-1}_{biomass}$. The mean and median CO_2 emissions intensities for willow were 3.2 g and 3.5 g CO_2eq $MJ^{-1}_{biomass}$, respectively. For poplar, the mean and median CO_2 emission intensities were identical: 5.4 g CO_2 $MJ^{-1}_{biomass}$ (Figure 4.4a). The intensities of GHG emissions ranged from 0.7 g to 10 g CO_2eq $MJ^{-1}_{biomass}$ for willow, while for poplar the range was 0.6 g to 1.9 g CO_2eq $MJ^{-1}_{biomass}$. The mean and median GHG emissions were higher for willow than for poplar (Figure 4.4b). Based on these data values and given the fact there was not enough data for a meaningful comparison, it is difficult to determine if the GHG as well as the CO_2 emission intensities of willow and poplar were similar. However, there was some evidence to suggest that these SRWC species might be comparable (Figure 4.4).

Irrespective of the differences among the reviewed studies and assuming that the intensity of GHG emissions from coal to be 96.8 g CO_2eq MJ^{-1}_{coal} [35], Figure 4.5 shows that SWRC reduce GHG emissions as compared to coal. The achievable GHG emission reductions ranged between 90% and 99%. This demonstrates that

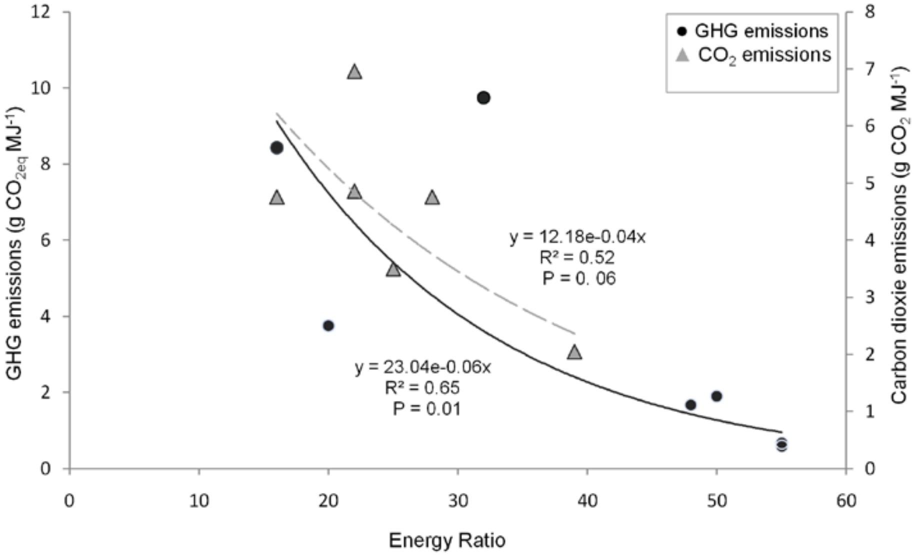

Figure 4.6 Carbon dioxide (triangle) and Greenhouse gas (GHG) (bullets) emissions as a function of energy ratio (ER). Each symbol (triangles and bullets) represents one specific study. The dashed and solid lines indicate the best fits through the data. R^2 represents the correlation coefficient; P = level of significance.

SRWCs reduce emissions and should therefore be part of an overall strategy for achieving the minimum target for GHG emissions reduction (i.e., 50%) in the year 2017 as required by the EU Renewable Energy Directive [36].

The intensities of CO_2 or GHG emissions were related to the ER for the reviewed studies as presented in Figure 4.6. The CO_2 or GHG emission intensity declined exponentially as the ER increased. This finding confirms the common knowledge that a reduction of GHG emissions can be achieved via reduced energy input into the system.

With regard to other environmental impacts -especially those that are characteristic of the agricultural phases of SRWC cultivation such as acidification and eutrophication- no average results can be provided because of the small number of cradle-to-farm gate LCA or EA studies that investigated these impacts. Nevertheless, one general observation can be made. For SRWCs, environmental impacts such as acidification and eutrophication seem to be low. The cradle-to-farm gate acidification impacts ranged from 15.7 mg to 23.5 mg $SO_2eq\ MJ^{-1}_{biomass}$. These values were 20 to 30 times lower than those of coal (476 mg $SO_2eq\ MJ^{-1}_{coal}$). The eutrophication impact values ranged from 2.4 mg to 3.3 mg PO_4eq $MJ^{-1}_{biomass}$. SRWCs performed slightly better in terms of eutrophication impacts as compared to coal (5.2 mg PO_4eq MJ^{-1}_{coal}).

12 Lessons to be learned

Our review revealed that the estimation of the energetic performance of bioenergy systems is complex. Not only the methodologies were different, but also various indicators were used for the evaluation of the energetic performance of bioenergy systems. These indicators prevented far-reaching conclusions from being drawn, discouraged a more transparent view of bioenergy systems, and did not facilitate immediate comparison of studies. As the results of LCA studies are increasingly being used to assist decision making at national and international levels, it is of the utmost importance to refine the ISO standards and to expand the LCA methodology with guidelines on indicators and methodologies to be used to estimate the energetic performance of bioenergy systems.

In the reviewed studies, fossil fuels (e.g., coal, natural gas) as well as biofeedstock *(Brassica carinata)* were used as reference systems. This picture however is incomplete. To make sure that bioenergy systems do not deplete the soil carbon stock, we recommend that the system boundary also includes a reference land use. With this system boundary it will be possible to compare the land on which the SRWCs are grown to previous land use.

With regard to energy balance, three variables were identified as the main sources of diverging results among reviewed studies: the amount and types of fertilizer used; harvesting method; and assumptions about the yield per hectare. With respect to GHG balance the divergent results were due to assumptions about N_2O emissions, the type of fertilizer used and its application rate, differences in the treatment of gases that contribute to GHG, and the system boundaries. Harmonized rules based on reasonable guidelines and assumptions on methodological issues, and how to deal with the associated uncertainty of key parameters would help to reduce the variability of LCA results.

Although the two studies that included the contribution of N_2O emissions from decomposition of leaves and litter in their assessments indicated a high contribution from decomposition of leaf-litter to GHG emissions (Table 4.4), it is, however, important to mention that all vegetation systems result in N_2O loss from leaf fall.

Also, given that leaves and litter accumulate on the soil surface, their decomposition in most cases will be aerobic, and the emissions of N_2O due to denitrification (an anaerobic process) will be minimized [32]. Consequently, it is not always relevant to include leaf-litter N_2O emissions – certainly not relevant to include all of it– in the LCA of bioenergy systems. For example, emissions from leaf-litter should not be accounted for when SRWC systems result in less litter and associated N_2O emissions compared with the reference land use. In contrast, emissions from leaf-litter should be accounted for when SRWC systems result in more litter and associated N_2O emissions compared with the reference land use.

Insights from this review indicated that carbon sequestration contributed to improve the GHG balance. However, there are situations when this factor (i.e., carbon sequestration) should not be accounted for in the analysis. This is the case when for example SRWCs displace land with high carbon stock such as grassland. In contrast, carbon sequestration should be accounted for when SRWCs displace cropland, and if the latter is not shifted to grassland. Carbon sequestration should also be accounted for when SRWCs are grown on abandoned land that exhibit low soil carbon stocks.

The cradle-to-farm gate results from statistical analysis showed that poplar and willow appeared to have similar mean yield and ER values while the results for the mean CO_2 and GHG emissions varied substantially. This indicates different assumptions about fertilizer emission rates, transport distance, and carbon sequestration between willow and poplar. The yield values demonstrated the smallest difference in the relative variability (IQR) between the two SRWC species. The ER also showed a much lower variation. One can therefore have confidence in the results that compared the energetic performance of willow and poplar because their ER was less wide-ranging.

Difficulties arose in the course of this review. Inventory data presented in some studies were incomplete and the sources of data were not specified. Also, very few studies presented a breakdown of the processes contributing to the energy input or to GHG impacts. We therefore recommend that future studies present complete inventory data, specify their sources, and when possible, make a breakdown of processes contributing to energy use as well as environmental impacts.

13 Conclusion

Despite the wide variation in specific numerical results among the reviewed studies, it is possible to draw the following conclusions: on average, SRWCs yielded 36 times more energy than coal (ER_{coal} ~ 0.9) per unit of fossil energy input, and GHG emissions were 24 times lower than those of coal (GHG_{coal} ~ 96.8 g CO_2eq MJ^{-1}_{coal}). Consequently, SRWCs provide an opportunity to reduce dependency on fossil fuels and to mitigate GHG emissions. Harvesting and fertilization were the largest contributors to energy use across the reviewed studies, and it was found that harvesting consumed 1.2% to 1.3% more energy than fertilization.

Despite the fact that SRWCs can play an important role in mitigating GHG emissions, some uncertainties linked to evaluating the GHG emissions from individual bioenergy systems remain. N_2O emissions from fertilizer application, carbon sequestration, and the reference land use (baseline) pose the major challenges to providing a high degree of confidence in the calculated emissions.

To reduce the high variability and create some more consistency in the future studies, harmonized rules based on reasonable guidelines and assumptions on methodological issues are needed. This could be achieved by limiting the freedom of choices for dealing with carbon sequestration. It should for example not be allowed to account for carbon sequestration in LCA when SRWCs displace land with high carbon stock such as grassland. Likewise, when SRWCs displace croplands, carbon sequestration should not be accounted for should the latter shift to grasslands. Conversely, carbon sequestration should be accounted for in LCA when SRWCs are grown on abandoned lands that exhibit low soil carbon stocks.

Efforts should also be made to develop a widely accepted framework toward a reliable analysis of energy efficiency of bioenergy production systems. Finally, more research is needed to address insufficient knowledge of the net GHG emission fluxes from bioenergy systems.

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ENERGY AND CLIMATE BENEFITS OF BIOELECTRICITY FROM LOW-INPUT SHORT ROTATION WOODY CROPS ON AGRICULTURAL LAND OVER A TWO-YEAR ROTATION

ENERGY AND CLIMATE BENEFITS OF BIOELECTRICITY FROM LOW-INPUT SHORT ROTATION WOODY CROPS ON AGRICULTURAL LAND OVER A TWO-YEAR ROTATION

Abstract

Short rotation woody crops (SRWCs) are a promising means to enhance the EU renewable energy sources while mitigating greenhouse gas (GHG) emissions. However, there are concerns that the GHG mitigation potential of bioelectricity may be nullified due to GHG emissions from direct land use changes (dLUCs). In order to evaluate quantitatively the GHG mitigation potential of bioelectricity from SRWCs we managed an operational SRWC plantation (18.4 ha) for bioelectricity production on a former agricultural land without supplemental irrigation or fertilization. We traced back to the primary energy level all farm labor, materials, and fossil fuel inputs to the bioelectricity production. We also sampled soil carbon and monitored fluxes of GHGs between the SRWC plantation and the atmosphere. We found that bioelectricity from SRWCs was energy efficient and yielded 200–227% more energy than required to produce it over a two-year rotation. The associated land requirement was 0.9 m^2 kWh_e^{-1} for the gasification and 1.1 m^2 kWh_e^{-1} for the combustion technology. Converting agricultural land into the SRWC plantation released 2.8 ± 0.2 t CO_2 ha^{-1}, which represented ~ 89% of the total GHG emissions (256–272 g CO_2 kWh_e^{-1}) of bioelectricity production. Despite its high share of the total GHG emissions, dLUC did not negate the GHG benefits of bioelectricity. Indeed, the GHG savings of bioelectricity relative to the EU non-renewable grid mix power ranged between 52% and 54%. SRWCs on agricultural lands with low soil organic carbon stocks are encouraging prospects for sustainable production of renewable energy with significant climate benefits.

Keywords direct land use change; eddy fluxes; life cycle assessment; energy ratio; GHG emissions

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1 Introduction

Renewable electricity represented 19.6% of the European Union (EU) grid mix power generation in 2009 [1]. Limited in natural resources, the EU imports large quantities of non-renewable fuels for its electricity production. Shifting electricity production away from non-renewable fuels towards renewable energy sources could increase the diversity of the generation mix, reduce the import bills, and help to mitigate climate change [2,3].

Biomass has the potential to provide non-intermittent renewable base-load electricity and thus could contribute to meeting the EU's renewable energy targets in 2020 [4–6]. Within the biomass portfolio, short rotation woody crops (SRWCs) with e.g. poplar *(Populus)* or willow *(Salix)* are candidates for large-scale application [7,8]. Compared to food crops SRWCs require low agrichemical inputs and less fertile land. Wood chips from SRWCs can be burned, gasified, or co-fired with coal to produce electricity. In addition to the non-renewable electricity offsets, SRWCs may also store carbon in agricultural soils [9,10], thus helping to reach the EU climate and renewable energy policy targets, whilst maintaining a reliable electricity system.

The greenhouse gas (GHG) performance of bioelectricity from SRWCs can also be affected by carbon stock changes due to land conversion from the previous land use. Converting agricultural lands to SRWC plantations may lead to losses of soil organic carbon (SOC) within the first two years following soil disturbance, although these changes are seldom statistically significant due to the high background variability in soil carbon stocks [10–12]. Such losses of carbon due to land use changes can compromise or even cancel the GHG saving benefits of bioenergy [13,14]. Also, biogenic methane (CH_4) and nitrous oxide (N_2O) emitted during crop production may outweigh the GHG benefits of SRWC-based bioelectricity [15]. Thus, an analysis of bioenergy impacts should consider its full life-cycle costs and benefits before policies aiming at large scale commercialization are adopted and implemented.

Much of the existing science on the energy and GHG performance of bioenergy has focused on liquid biofuels [16,17] with fewer studies investigating the energy and GHG balances of bioelectricity from SRWCs [18–22]. The majority of these studies in turn have concentrated on CO_2 emissions from fossil fuel combustion during management activities rather than biogenic GHG emissions from land use change. Direct land use change (dLUC) emissions have been particularly neglected [23], even

though the initial loss in soil organic carbon (SOC) as well as emissions of CH_4 and N_2O from agricultural soils may be substantial [24]. Moreover, the accounting of farm labor inputs, and land requirement are missing in earlier studies. Furthermore, the lack of reliable measurements of GHG fluxes (CO_2, CH_4 and N_2O) during the SRWC production increases the degree of uncertainty of previous estimates.
Here we report and document quantitative data on the land requirement, energy yield and GHG offsets of bioelectricity production from SRWCs on former agricultural land. In order to obtain quantitative data on the land requirement, energy yield, and GHG offsets of bioelectricity from SRWCs, we managed an industrial-sized SRWC plantation for bioelectricity production without supplemental irrigation or fertilization for two years. We included all energy and GHG emissions incurred during the production and conversion of biomass from SRWCs to bioelectricity.

2 Materials and Methods

2.1 Site location, soil carbon, and plant material

An operational SRWC plantation was installed in Lochristi, Belgium (51°06′N, 3°51′E, 6.25 m asl). The long-term mean annual temperature was 9.5 °C and the average rainfall was 726 mm a^{-1} [25]. The soil texture in the top 30 cm was 86.8% sand, 11.4% clay, and 1.8% silt with a mean pH of 5.51 (Table 5.S1). The region of the site is considered to be a sandy region with a poor drainage [26]. Historically, the site was cleared of the original forest in the early 20th century and has since been under agricultural land use, regularly plowed and fertilized at 200 kg N ha^{-1} for production of cereals (wheat and maize) and tuberous (potatoes) crops. Prior to deep plowing, we carried out detailed soil survey in March 2010 by analyzing soil samples taken at 110 locations, uniformly distributed over the agricultural land. Soils were sampled to a depth of 15 cm using core sampling. The conversion of the agricultural land to a SRWC plantation began on the 26th March 2010 with the application of glyphosate (3.5 l ha^{-1}) to the soil, followed by deep plowing (up to 70 cm depth), and flattening before planting (Table 5.1). In April 2010, the SRWC plantation was established on 18.4 ha of this former agricultural land (Figure 5.S1). Twelve poplar and three willow genotypes representing different species and hybrids of *Populus deltoides*, *P. maximowiczii*, *P. nigra* and *P. trichocarpa* and *Salix viminalis*, *S. dasyclados*, *S. alba* or *S. schwerinii* were planted at a density of 8000 cuttings ha^{-1}. During the first months after planting, chemical, mechanical, and manual weed controls were performed as SRWCs are exposed to weed competition during the first growing season. No irrigation or fertilization was applied in this SRWC plantation. Before harvesting in 2012, we resampled the soil to 15 cm depth at 16 sampling points, with each point located less than 40 m from one of the eight selected sampling points of the initial soil survey of March 2010 [27]. All soil samples were oven-dried at 60 °C for 72 h and analyzed for soil carbon concentration in an elemental analyzer (Carlo Erba Instruments, Italy). The SOC stock was estimated by multiplying the SOC content of the first 15 cm by the bulk density of that soil layer (Table 5.2).

Table 5.1 General inventory data for the production of short rotation woody crops. The columns from left to right denote the field activities, the implement used, tractor used, the total operating time, total fuel consumption, the area covered, and the material inputs.

Activities	Implement used		Tractor used		
	Type	Weight (kg)	Type	Weight (kg)	Power (kW)
Chemical treatment	HBS	800	Fendt V 415	7000	119
Deep plowing	PF	820	Fendt V820	9000	157
Plowing	CP	820	Fendt V820	9000	157
Flattening	R	716	Fendt V415	7000	119
Planting	LP	600	Massey F6480	5000	97
Application of PPEH	HBS	800	Fendt V415	7000	119
Application of PEH	CBS	200	Iseki TU 165	400	12
Application of PEH	CBS	200	Iseki TU 165	400	12
Application of PEH	HBS	800	Fendt V415	7000	119
Mechanical weeding	ST	500	Fendt V712	5000	97
Mechanical weeding	GS	–	GS. FS 400	8	1.9
Mechanical weeding	GM	–	GM Rapid Euro	237	14.6
Mechanical weeding	HDM	–	HDM	78	3.2
Manual weeding	–	–	–	–	–
Harvesting	E–harvester	7000	JD 6920T	14000	110

The data were collected on-site. HBS: Hardy bomb sprayer; HDM: heavy duty machine, GM: grass mulcher, CBS: custum build sprayer, LP: leek planter, R: roller; PF: Plow 4 furrow, GS: grass strimmer, E-harvester: energy harvester, CP: chilser plow; ST: Steketee; JD: John Deere, PPEH: pre-emergent herbice, PEH: post emergent herbicide. Deep plowing, plowing and flattening have been grouped into land preparation.

Table 5.2 Soil carbon stocks at depth of 15 cm and change in carbon stock due to land conversion from agricultural land to SRWC plantation. The positive value of the relative change in SOC stock denotes a loss (significant at $p < 0.001$) in carbon.

Land use type	Sampling depth (cm)	Bulk density (kg m^{-3})	Carbon conc. (kg C kg^{-1} soil)	Total carbon (t C ha^{-1})	$\Delta SOC_{2010–2012}$ (t C ha^{-1})
Agricultural (2010) (n =8)	0 -15	1298±169	0.015±0.004	28.38±7.07	7.59±7.81
SRWC plantation (2012) (n =16)	0 -15	1519±59	0.009±0.002	20.79±3.33	

SOC: soil organic carbon; SRWC: short rotation woody crop, $\Delta SOC_{2010–2012}$: change in soil organic carbon, n: number of samples

Total operating time (h)	Total fuel consumption (l)	Total lubricant consumption (l)	Coverage (%)	Input rates (unit ha^{-1})
2.5	42	0.3	32	3.5 l
5.5	105	2.1	32	–
17.0	285	5.0	100	–
13.5	242	4.4	100	–
50.0	302	5.2	78	8000 cuttings
3.0	54	0.9	78	0.3 l AZ500
15.0	32	0.1	33	1 l Tomahawk
15.0	32	0.1	38	1 l Matrigon
2.5	45	0.8	78	2.5 l Aramo
40.0	120	1.7	78	–
198.3	28	–	62	–
69.7	45	–	62	–
14.1	28	–	62	–
–	–	–	78	49.1 h
23.8	710	1.0	78	–

2.2 GHG flux data

Greenhouse gas flux measurements were carried out from June 2010 to December 2011 using the eddy covariance (EC) method. The EC system consists of a 3-D sonic anemometer, a closed-path CO2/H_2O analyzer (Li-700, Li-Cor Inc.), and closed-path N_2O/CO (Los Gatos-908, Los Gatos Research), and CH_4 (Los Gatos DLT-100, Los Gatos Research) analyzers mounted on a 5.8 m high micrometeorological flux tower, in the plantation (Figure 5.S1). Raw data were recorded at a 10 Hz sampling rate; momentum, energy, CO_2, N_2O, and CH_4 fluxes were derived. The CO_2, N_2O and CH_4 fluxes were then converted to densities using a CR5000 data logger. Data processing was done following the generally accepted EC protocols [28] including among others a 2D coordinate rotations of wind components. The EC fluxes were calculated as the mean covariance between CO_2, N_2O, and CH_4 concentrations and fluctuations in the vertical wind speed over 30 min after removing spikes in raw data and corrections for air density fluctuations [29]. Individual data points were removed when the following criteria were met: (i) for CO_2 and for the wind velocity components (u, v and w) when the standard deviation of the 30 min mean was higher than 10, for N_2O when it was higher than 8, for H_2O when it was higher than 1, for CH_4 when it was higher than 0.3; (ii) when CH_4 and N_2O minimum concentrations were less than zero, and (iii) when data points came from outside of the footprint of interest (wind direction between 50 °C and 250 °C) [30,31]. Gaps in data were filled using different techniques. For CO_2 data the method of Reichstein et al. [32] was applied. As no standard gap-filling method exists for CH_4 and N_2O, fluxes of CH_4 and N_2O were linearly interpolated in periods with similar emission rates [33]. An overall annual GHG budget was computed by cumulating the net ecosystem exchange (NEE), N_2O, and CH_4 over each year of the study. CO_2, CH_4 and N_2O were converted to CO_2 equivalent using the IPCC conversion factors [34]. A more detailed description of EC flux calculations can be found in Zona et al. [35].

2.3 Life cycle assessment

To identify and compare the GHG emissions of the investigated bioelectricity system to those of the EU non-renewable grid mix electricity generation (reference system), a life cycle assessment (LCA) was performed. In this analysis, the functional unit was 1 kWh_e of bioelectricity. We included all relevant processes of bioelectricity production – from agrichemicals production, land preparation, planting, weeding,

harvest and chipping, to the final conversion of chips to electricity – and all transportation needed within the system boundary (Figure 5.1). Capital equipment was also included. Since irrigation and fertilization were not applied in this plantation, the unit processes of irrigation and fertilizer production and application were excluded from the system boundary. Moreover, the agricultural land in this study was not in conservation tillage; therefore, carbon was not being stored in the soil prior to its conversion to SRWC plantation. The foregone carbon sequestration (i.e., the ongoing carbon storage that is given up by devoting the agricultural land in this study to the production of SRWCs for bioelectricity) was zero and therefore not included in the system boundary.
The system boundary of the EU non-renewable grid mix electricity generation included the extraction, transport, refining, storage, and conversion of non-renewable fuels to electricity (Figure 5.1). Environmental impacts were based on the Impact 2002 + method [36], and were limited only to land requirement, energy requirements, and GHG emissions of the bioelectricity production. LCA modeling was performed in Simapro 7.1 [37]. Furthermore, the energy ratio and GHG savings of the system were assessed.

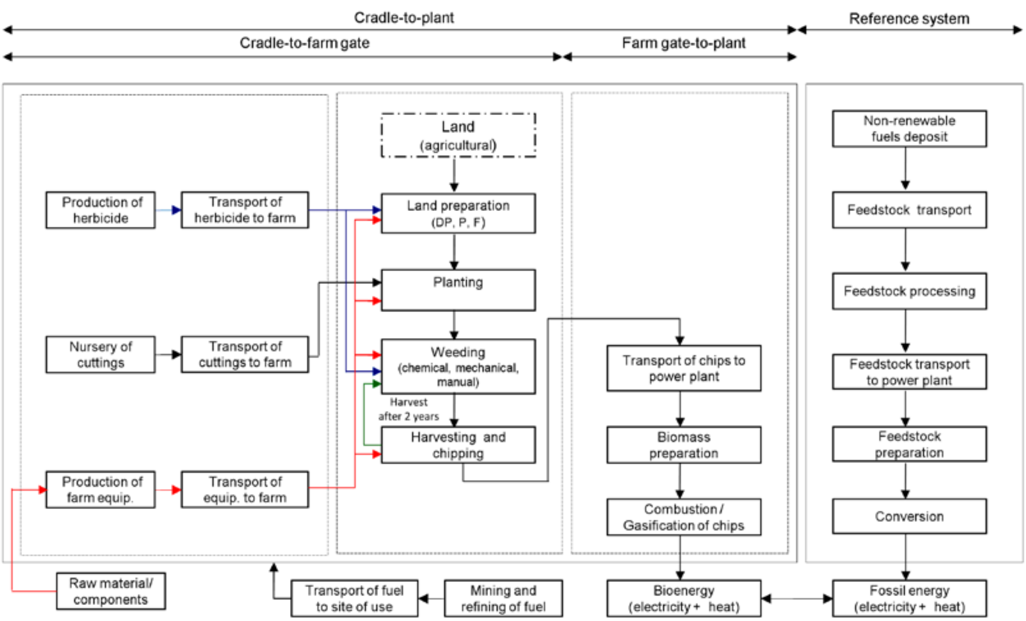

Figure 5.1 System boundary of the bioelectricity production as well as of the EU non-renewable grid mix electricity used in this study. The boxes represent unit processes (or activities) and the arrows refer to material and energy flows. The solid lines represent the system boundary. Land preparation includes: deep plowing (DP), plowing (P), and flattening (F).

2.3.1 *Management input data*

We inventoried all activities of the SRWC biomass production in the field (Figure 5.1). Using a book keeping method we measured the amount of diesel and lubricant consumed to carry out each activity (e.g., plowing, weeding, planting, and harvesting). We also quantified the types and amount of chemicals used for weeding, as well as the amount of cuttings used in the SRWC biomass production. Besides, we collected data on the lifespan, weight of implements and tractors used, and operating time for each farming activity (Table 5.1). In addition, we collected data on the production of cuttings (Table 5.3). We also gathered data on vehicle types (truck or van), weights carried, and the distance travelled to transport farm materials (e.g. chemicals and cuttings) and tractors from the regional storage facilities to the SRWC plantation (Table 5.S2). We further assumed the trucks or vans returned empty. Solar energy, which drives the build-up of SRWC biomass, was excluded from the system boundary. However, unlike in most studies, the human labor input for manual weeding was considered. To estimate the human energy input, we quantified the amount of person-hours of labor for manual weeding (Table 5.1), and multiplied it by the energy expended (1.9 MJ h^{-1} [38]) by a male worker to carry out manual weeding. No attempt was made to include the human labor associated with manufacturing of farm equipment and agrichemicals. All agricultural input data were collected in the field and referred to the 2010–2012 operations.

2.3.2 *Data on energy conversion technologies and allocation method*

We assumed that the woody biomass chips were used in combined heat and power (CHP) plants. Two existing CHP plants were modelled for converting SRWC chips to bioelectricity: (i) a gasification plant which gasified 35.5 kton a^{-1} of dried SRWC chips at 30% moisture to produce 40.2 GWh_e a^{-1} at 27.5% efficiency, and (ii) a combustion plant that burned 31.3 kton a^{-1} of dried SRWC chips at 30% moisture to produce 25.9 GWh_e a^{-1} at 22% efficiency (Table 5.S3). Bioheat is also produced during power generation in CHP plants (Table 5.S3). Since bioheat has a positive economic value and displaces heat that would otherwise be supplied from other sources, inputs (e.g. land and energy use) and outputs (GHG emissions) need to be allocated between bioelectricity and bioheat. We used the exergy-based allocation to partition inputs/outputs between bioelectricity and bioheat. First, we assumed an ambient temperature of 10 °C (283 °K) and a steam temperature of 120 °C (393 °K) for both the gasification and combustion.

Table 5.3 Inputs for the production of SRWC cuttings. The column from left to right denote the field activities, the implement used, tractor used, the operating rate, total fuel consumption. These data are based on 1 ha land use and 15000 plants at the nursery. The annual average production of cuttings (only 3 harvests) is 153300 cuttings per hectare.

Activities	Implement used		Tractor used			Operating rate	Total fuel consumption	Input rates
	Types	Weight (kg)	Types	Weight (kg)	Power (kW)	(h ha^{-1})	(l)	(unit ha^{-1})
Plowing	4 Furrow	1800	Fendt	6000	104	2	24	-
Flatening	Roller	1200	Fendt	6000	104	1.5	18	-
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	80 kg N
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	100 kg P
Fertilising	Sprayer	100	Lamborghini	1150	31	1	7	60 kg K
Fertilising	Sprayer	1000	Fendt	6000	104	1	11	1000 kg $CaCO_3$
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l AZ 500
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l Kerb50
Chemical weeding	Sprayer	100	Lamborghini	1150	31	1	7	1 l Basta
Mechanical weeding	-	130	Deutz Agrocompacts	2150	45	2.5	20	-
Manual weeding	-	-	-	-	-	-	-	65 h

Note: The data were obtained from the Research Institute for Nature and Forest (INBO). SRWC: short rotation woody crop.

Next, we estimated the Carnot factor as indicated in Table 5.S4, and then calculated the bioheat exergy by multiplying this Carnot factor (i.e. 0.27) by the annual amount of bioheat produced by the gasification (83.9 GWh) and combustion (82.3 GWh) technologies, respectively. For bioelectricity, we assumed the exergy is equal to its energy content and thus the share of bioelectricity of the total delivered exergy (Table 5.S4).

2.3.3 Energy balance and GHG savings

All the collected data were normalized to the functional unit (i.e., 1 kWh_e), entered into Simapro 7.1, and modeled into environmental inputs and outputs. Simulation results were then exported from Simapro 7.1 to an Excel spreadsheet where calculations of the energy balance and GHG savings were performed. We calculated the energy ratio by dividing the energy content of bioelectricity output (i.e., 1 kWh_e = 3.6 MJ_e) by the sum of all fossil energy inputs needed to produce one unit of bioelectricity. To estimate the GHG emission savings, we first multiplied the emission factors of electricity from natural gas, coal, uranium, and oil derived from Ecoinvent [39] by the fraction of natural gas fired (29%), coal burning (32%), nuclear (35%), and oil fired power (4%) making up the EU non-renewable grid mix electricity in 2009 [40]. We then summed-up these products to obtain the GHG emission rates for the EU non-renewable grid mix electricity in 2009 (Table 5.S5). Finally, we estimated the GHG emission savings by comparing the GHG emission rates for the SRWC-bioelectricity chain to that for the grid mix electricity in the EU in 2009.

3 Results

3.1 Biomass yield

The mean yield after two years of growth was 4 ton ha^{-1} a^{-1}. Considerable tree mortality (~18%) was observed in the establishment year [41]. Because tree mortality was evenly distributed across the plantation, and established trees occupied the vacant spaces, no large gaps occurred. At the end of two years of growth, about 114 tons of biomass were harvested from 14.2 ha and transported to the bioelectricity plant. The chemical composition and the measured heating value (19.5 MJ kg^{-1}) of the harvested SRWC chips from our plantation are summarized in Table 5.S6.

3.2 Energy requirement and energy ratio

The total energy input to produce one unit of bioelectricity was 1.1 MJ kWh_e^{-1} for the gasification and 1.2 MJ kWh_e^{-1} for the combustion technology. The breakdown of the total energy input across the different components of the bioelectricity production is shown in Figure2. Land preparation was the activity that consumed the most energy (24%), followed in decreasing order by harvesting (20%), production of cuttings (18%), weeding (17%) and planting (10%). The contribution of cutting production to the total energy input was high because the production of SRWC cuttings covered only three harvests. Facility construction and transport were the activities that consumed the least amount of energy (Figure 5.2). For both conversion technologies (gasification and combustion), the energy output was much higher than the total energy inputs to produce 1 kWh_e of bioelectricity. The energy ratio (ratio of the energy content of 1 kWh_e = 3.6 MJ_e of bioelectricity over the total energy input for its production) was 3 for the combustion and 3.3 for the gasification technology (Figure 5.2). Thus, the bioelectricity from SRWCs yielded 200–227% more energy than the energy invested in its production.

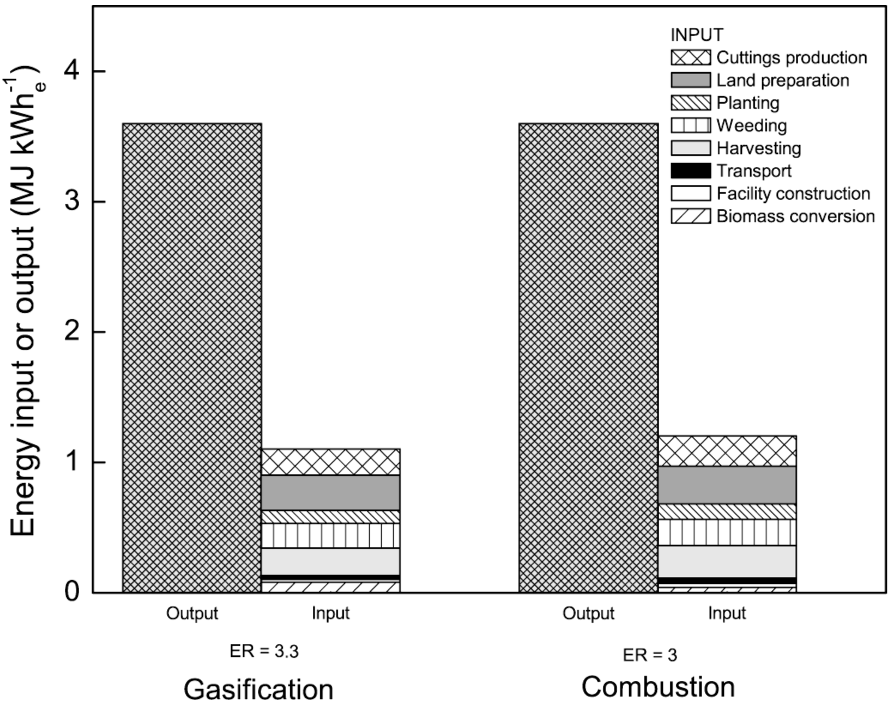

Figure 5.2 Energy balance of the biomass gasification (left) and biomass combustion (right) technology investigated in this study. The black bars represent the energy output whereas the stacked bars represent the energy input items of each biomass conversion technology. *Land preparation includes: deep plowing, plowing, and flattening.* ER: energy ratio (output-input ratio). Data presented are based on a biomass yield of 4 odt ha^{-1} a^{-1}, and a single two-year rotation which includes only one harvest.

3.3 Cumulative dLUC emissions

Conversion of agricultural land to a SRWC plantation resulted in a loss of SOC of ~ 27.8 ± 9.6 ton CO_2eq ha^{-1} in the top 15 cm of soil over the two-year period (Table 5.2). The cumulative NEE measured by eddy covariance is shown in Figure 5.3. High amounts of CO_2 were released after the plantation establishment in 2010 and during the autumn-winter period, whereas much of the CO_2 uptake by the SRWC canopy occurred during the growing season. Integrated over the measuring period, the cumulative NEE which also includes the loss of SOC was -0.8 ± 0.6 ton CO_2eq ha^{-1} (Figure 5.3). This suggests that the SRWC plantation was a sink of CO_2 despite the initial loss in SOC. No seasonal trends in N_2O and CH_4 fluxes were observed in this study during the entire measurement period. Most of the N_2O emissions occurred in July-August 2010, and the cumulative amount changed very little thereafter. CH_4 fluxes were very small throughout the measurement period (Figure 5.3). The cumulative N_2O and CH_4 emissions were 2.39 ± 0.52 ton CO_2eq ha^{-1} and 1.12 ± 0.07 ton CO_2eq ha^{-1}, respectively (Figure 5.3). These positive cumulative fluxes more than offset the CO_2 uptake, and turned the SRWC plantation from a net CO_2 sink into a small source of GHGs. At the end of the study period, the cumulative dLUC GHG emissions, taking into account the CO_2, N_2O and CH_4 fluxes, amounted to 2.8 ± 0.2 ton CO_2eq ha^{-1} (Figure 5.3). This indicates that N_2O and CH_4 played an important role in GHG emissions associated with dLUC at our site. Thus, the soil N_2O and CH_4 fluxes may reduce the potential sink strength of SRWC plantations during the first two years of culture.

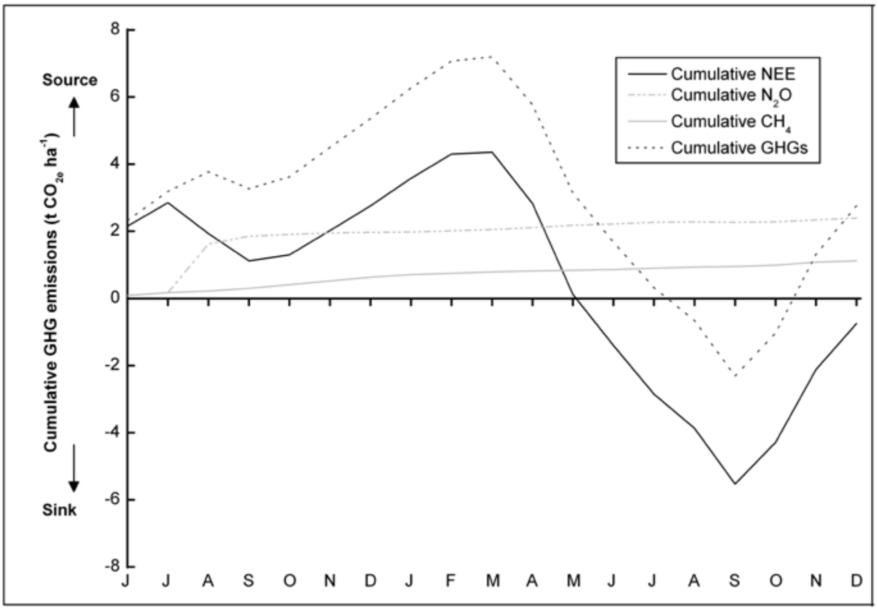

Figure 5.3 Cumulative GHG fluxes over the measuring period (2010–2011). The NEE is represented by the black line, N_2O fluxes by the dash-dot grey line, CH_4 fluxes by the light grey, whereas the cumulative GHGs is represented by the dotted grey line. Positive values denote the loss from ecosystem and negative values denote uptake. GHGs: greenhouse gases, NEE: net ecosystem exchange, N_2O: nitrous oxide, CH_4: methane.

3.4 GHG emissions and savings of bioelectricity

The combustion of SRWC chips in an existing biomass-fired power station resulted in a total GHG emission of about 272 g CO_2eq kWh_e^{-1}. The gasification of these chips showed a lower total GHG emission of ~256 g CO_2eq kWh_e^{-1} (Figure 5.4). For both the gasification and the combustion technology, dLUC accounted for 89% of the total GHG emissions, while the emissions from all the other processes associated with bioelectricity production made-up the remaining fraction (11%) (Figure 5.4). The GHG emission reduction compared to the EU non-renewable grid mix electricity was 52% for the combustion and 54% for the gasification technologies. The GHG savings even reached 67% and 69% for the combustion and gasification technologies, respectively, when the EU fossil fuels grid mix electricity (i.e., excluding nuclear power) was considered as a baseline (Figure 5.4). Therefore, converting agricultural land into a low-input SRWC plantation did not negate the GHG emission benefits of bioelectricity production regardless of the conversion technology chosen and of the EU grid mix electricity displaced.

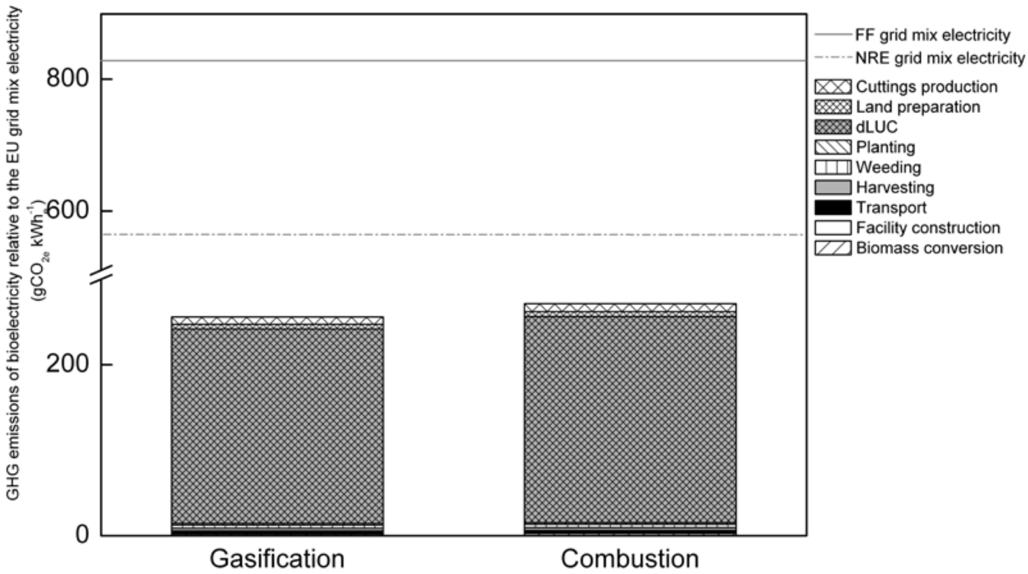

Figure 5.4 Greenhouse gas emissions relative to the EU non-renewable and fossil fuels grid mix electricity. The bars represent the total GHG emission of each bioelectricity production technology whereas the dotted- and solid lines above the bars represent the GHG emission of the EU non-renewable as well as fossil fuels (i.e., excluding nuclear power) grid mix electricity production respectively. *Soil preparation includes: deep plowing, plowing, and flattening.* Data presented are based on a biomass yield of 40dt ha^{-1} a^{-1}, and a single two-year rotation which includes only one harvest.

3.5. Land requirement

The total land requirement for bioelectricity production was 1 m^2 kWh_e^{-1} for the combustion and 0.9 m^2 kWh_e^{-1} for the gasification technology (Figure 5.S2). For both the combustion and the gasification technology, the land requirement of the SRWC chips accounted for 95% of the total land requirement while the land needed for the production of cuttings used in the site establishment accounted for only 5% of the total land requirement (Figure 5.S2). Because of its high electrical efficiency, gasification reduced the total land requirement by 10% compared to combustion technology. This reduction suggests that conversion efficiency played a considerable effect on the land requirement.

4 Discussion

The biomass yield was 50–60% lower than the average attainable yield in Europe (8–10 ton ha^{-1} a^{-1}) [42], which may be explained by the young age of the plantation, the soil type, the low planting density, and possibly other factors such as weather and weed pressure. It has been shown that SRWC stands invest more in their root systems and less in aboveground growth early in stand development [43,44]. Moreover, unlike in most European studies, neither fertilizer nor irrigation was used at our site. Given that the number of shoots per stool and stem diameter usually increase between the first and subsequent harvests [45], an increase in yield is likely in the second harvest of our SRWC plantation.

Our bioelectricity production systems yielded 200–227% more energy than required for its production, which implies that bioelectricity from SRWCs grown on agricultural land is a valuable energy substitute, and producing more bioelectricity from SRWCs could displace non-renewable fuel imports, which would increase energy security. The high net energy yield of bioelectricity from SRWCs in this study was attributable to the low inputs (no fertilization and no irrigation) during the feedstock production phase and the use of bioheat as a co-product of bioelectricity production. All recent studies showed that bioelectricity from SRWCs has a positive energy balance, and reported energy ratios ranged from 3 to 16 [46]. Our results, even though they are for a single two-year rotation with only one harvest, are consistent with other studies that show that bioelectricity has a positive energy balance. However, our estimated energy ratio (3-3.3) was at the lower end of this range. The main reason for the low energy ratio estimate is the low biomass yield during the first two years of tree growth.

The loss of SOC from the SRWC plantation may be attributed either to decreased organic inputs to the soil relative to decomposition early in the SRWC establishment [47] or to the effect of tillage during site preparation which renders more SOC vulnerable to decomposition and thus triggered the release of SOC [48]. Carbon dioxide fluxes showed high seasonal variability, driven primarily by the SRWC response to seasonal changes in temperature and soil moisture (Figure 5.3). Nitrous oxide fluxes were high, in which a peak emission of ~60% of the annual N_2O flux occurred after a single rainfall event in August 2010 (Figure 5.3). The high N_2O emissions were contrary to what we expected given that our SRWC plantation was unfertilized. A likely explanation is that decades of intensive fertilization and very high atmospheric N deposition – due to high ammonia and nitrogen oxides from dense livestock and traffic, respectively, in Flanders – led to a high N content of the soils (9.3 ton N ha^{-1}) some of which could not be fixed by plants and was converted to N_2O during nitrification and denitrification processes. The observed fluxes also showed that our SRWC plantation was a source of CH_4. These CH_4 fluxes could be attributed to a high water table and low atmospheric evaporative demand at our site in winter, causing soil saturation, favoring methanogenesis and restricting the oxidation of CH_4 by methanotrophs.

The cumulative dLUC GHG emissions occurring during the two-year rotation was 2.8 ± 0.2 ton CO_2eq ha^{-1} (Figure 5.3), indicating that the SRWC plantation was a net source of GHGs due to low biomass yield, and low input from leaf litter and root turnover relative to soil carbon loss. However, it is likely that our SRWC plantation may become a net sink of GHGs in the longer term. In fact, Arevalo et al. [11] showed that at least four years were necessary for a SRWC plantation on croplands to reach its pre-plantation carbon level and become a net sink of GHGs. Our estimate of dLUC GHG emissions was much lower than that for conversion of grassland to a corn plantation (~12 ton CO_2eq ha^{-1}) [49], and for establishment of fertilized SRWCs on pastureland (7–11 ton CO_2eq ha^{-1}) [50], and lower than for conversion of abandoned cropland to prairie biomass (~6 ton CO_2eq ha^{-1}) [13]. Our estimate of dLUC GHG emissions was low because the SRWC plantation was established on agricultural land that contained depleted SOC pools due to repeated tillage. Thus, our dLUC estimate was limited only to emissions from soil disturbance during land preparation. The total GHG emissions of bioelectricity production (256–272 g CO_2eq kWh_e^{-1}) in this study were well above the maximum values (39–132 g CO_2eq kWh_e^{-1}) reported in [46] because of the inclusion of dLUC GHG emissions in our system boundary. Also, differences in SRWC yields, assumptions about efficiencies of conversion technologies, as well as the allocation method used in this study partly explained the differences with previous analyses. When leaving out the contribution of dLUC (~89% of total GHG emissions), our estimate of GHG emissions from bioelectricity fell to 29–31 g CO_2eq kWh_e^{-1}. This latter range compared well with estimates reported in [46] since dLUC emissions were ignored in all articles reviewed in that study. On a kWh_e basis, bioelectricity from SRWCs on agricultural lands reduced emissions by at least 52–54% compared to the current EU non-renewable grid mix power (Figure 5.4). Thus, despite entailing dLUC GHG emissions (Figure 5.4), bioelectricity still provided immediate GHG benefits because SRWCs were grown on agricultural lands and were converted to electricity using efficient technologies.

The EU has committed to producing 20% of consumed energy from renewable energy sources by 2020 [4]. To meet this target, it has been projected that about 232 TWh_e would come from biomass [51]. Considering that it takes about ~1 m^2 kWh_e^{-1} electricity (Figure 5.S2), and assuming that electricity from cultivated woody biomass represents 15% of the projected amount [52], about 34800 km^2 of land (~2% of the EU's

Table 5.4 Sensitivity analysis of key parameters on results.

Parameters	Scenario	Gasification Land requirement (m^2 kWh_e^{-1})	Energy demand (MJ kWh_e^{-1})	GHG emissions (gCO_2 kWh_e^{-1})
Yield	Increase +100%	0.452	0.575	130.2
Electrical conversion efficiency	Increase +20%	0.8	0.9	213.3
	Decrease -20%	1.1	1.4	298.2
Initial carbon stock	Increase +20%	na	na	300.0
	Decrease -20%	na	na	211.9
Allocation method	Energy approach	0.5	0.6	128.1

NB: 100% decrease in yield makes no sense and was therefore not considered in sensitivity analysis. na: not applicable total utilized agricultural area) would be required to meet the EU 2020 bioelectricity target from cultivated woody biomass. Unless yield of food crops is increased on existing croplands to meet the growing food and feed demand, it may be difficult to devote ~ 2% of EU's utilized agricultural land to SRWCs. However, yield increase in the future years has the potential to decrease the land requirement for SRWCs [53,54].

A number of sensitivity analyses were carried out to assess the influence of some key inputs variables and assumptions and the robustness of the obtained results. The elasticity method (i.e., the ratio of the change in the results to the change in data) was used to perform the sensitivity analysis. When the biomass yield (4 ton ha^{-1} a^{-1}) in this study was doubled, we found that the energy demand and GHG emissions of bioelectricity production were reduced significantly (Table 5.4). A sensitivity analysis on initial SOC content revealed that, even if SRWCs were grown on an agricultural land containing 20% more SOC than at our site, the overall GHG reduction would still be 44–47% relative to the current EU non-renewable grid mix power (Table 5.4). We also hypothesized a case where the electrical conversion efficiencies of both the gasification and combustion were reduced by 20%. In that scenario, we found that the land requirement would increase by 10% while the energy ratio and the GHG saving would decrease by a similar percentage. But bioelectricity would still provide energy and GHG benefits (Table 5.4). Finally, when the energy-based allocation method was adopted, the land requirement, energy demand, and GHG emissions of bioelectricity were strongly reduced for both conversion technologies (Table 5.4).

Combustion		
Land requirement (m^2 kWh_e^{-1})	Energy demand (MJ kWh_e^{-1})	GHG emissions (gCO_2 kWh_e^{-1})
0.481	0.622	140.6
0.8	0.9	227.1
1.2	1.4	316.8
na	na	318.2
na	na	225.4
0.4	0.5	121.4

4.1 Limitations and cautions to the interpretation of results of this study

One limitation of the current study is that it only addresses the dLUC GHG emissions of bioelectricity. However, growing SRWCs on agricultural lands for bioelectricity may trigger land conversion elsewhere in the world, releasing GHGs through indirect land use (iLUC) [14,55–57]. Therefore, a complete assessment needs to include both dLUC and iLUC. Another limitation is that this study considers only SRWCs from tilled agricultural land. Grassland, non-tilled agricultural land as well as set-aside lands are currently a sink of GHGs [58,59]. Consequently, converting these lands to SRWC plantations would result in significant dLUC GHG emissions, which in turn would result to little or no GHG savings. Thus, our study likely understates the disadvantage of bioelectricity production relative to facilities that would obtain SRWCs from set-aside or grasslands. Finally, our study assesses the life-cycle of existing bioelectricity technologies that currently have low to medium electrical efficiency. The adoption of advanced gasification/combustion technologies (i.e. $\eta_e \geq 35$) changes the results of this analysis. Thus, the land requirement, energy demand, and GHG emissions reported here reflect today's average technologies. Despite these limitations, our study suggests that (i) in areas where SRWCs can be grown sustainably, even with low yields and one two-year rotation, there is a positive energy balance; and (ii) bioelectricity would contribute to GHG mitigation in the power sector if appropriate lands, feedstock, and the correct conversion technologies were used, and if the SRWC plantation was maintained as a low-input system.

5 Conclusion

By combining field measurements and a LCA approach we showed that a low input SRWC plantations on agricultural lands for bioelectricity production resulted in immediate GHG savings relative to grid mix electricity. Consequently SRWCs that come from agricultural land with low carbon stocks are an encouraging prospect for sustainable production of renewable energy with significant climate benefits.

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Annex: Supplementary Information

Additional information on inventory data for: transport, GHG emissions of the EU non-renewable grid mix electricity, conversion technologies, chemical composition and heating value of SRWC chips, allocation method, as well as information about the soil texture and map of the site can be found in the supplementary information.

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Annex: Supplementary Information

1 Material and Methods

1.1 Location

A comprehensive attributional life cycle assessment was performed to evaluate and document the energetic performance and greenhouse gas (GHG) emissions of bio-electricity from short rotation woody crops (SRWCs) relative to a reference system. The SRWC plantation was established in April 2010 on a former agricultural land in Lochristi, Belgium (51°06′N, 3°51′E, 6.25 m asl). Poplar and willow clones were planted in the field at a planting density of 8000 cuttings ha^{-1}. A schematic design of the plantation is shown in Figure 5.S1. The soil texture of the former agricultural land before its conversion to SRWC plantation is given in Table 5.S1.

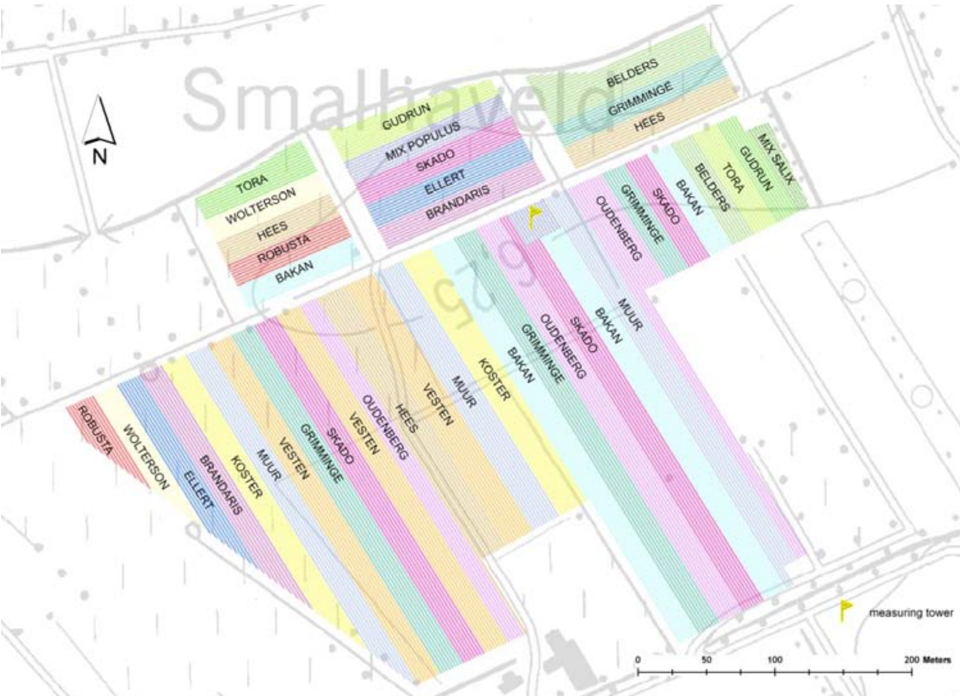

Figure 5.S1 Design of the SRWC plantation. The different coloured bars represent the rows occupied by poplar and willow clones. The flag denotes the position of the eddy covariance measuring tower.

Table 5.S1 Soil texture of the agricultural land before its conversion to SRWC plantation

Land type	Soil texture				
	Clay	Silt			Sand
	< 2µm	[2–10 µm [	[10–20 µm [	[20–50 µm [	> 50 µm
Agricultural	11.4	0.6	0.4	0.8	86.8

1.2 System boundary and inventory data

The system boundary includes the cultivation, harvesting, and conversion of SRWC to bioelectricity. The system boundary also includes sub-processes such as the production of chemicals, cuttings, farm equipment, and crude oil extraction. The function of the bioelectricity system is to generate electricity for EU consumers. The chosen functional unit was 1 kWh_e and the amounts of SRWC chips at 30% moisture required to deliver the functional unit via combustion (η_e = 22%) and via gasification (η_e = 27.5%) were 1.21 kg and 0.88 kg respectively. The geographical borders of this study was limited to Europe (for materials and chemicals production) and to the EU (for the production and conversion of SRWCs to bioelectricity). The temporal boundary of this study was from 2010 to 2012, the period representing the time horizon of the majority of the data collected. Data for production and use of SRWCs reflect the period stated. The impacts categories considered included energy requirement, GHG emissions, and land use.

We collected all input and output data associated with the production of the functional unit (1 kWh_e). Primary data were collected on-site via measurements or questionnaires while secondary data were derived from the literature. Where no data were available, the Ecoinvent database [1] was used. Table 5.S2 and Table 5.S3 list the data on transport and conversion technologies used in this study. All collected data (including those in the manuscript) were normalized to the functional unit, imported into Simapro 7.1, and modeled into environmental inputs and outputs.

Table 5.S2 Transportation data. The columns from left to right denote the product transported, the weight, transport mode, and the distance travelled.

Product transported	Weights	Mode of transport	Distance travel
Cuttings to Belgium	1.2 ton	40 ton truck	150 km
Cuttings to the SRWC plantation	1.3 ton	Van < 3.5 ton	60 km
Chips to power plant	114 ton	40 ton truck	20 km
Harvesters to SRWC plantation	14 ton	40 ton truck	30 km

SRWC: short rotation woody crop.

Table 5.S3 Power plant input/output and performance data. The columns from left to right denote, the different inputs and output and the types of biomass conversion technology.

Items	Biomass Gasification with Gas Engine [2]	Biomass Combustion with Steam Turbine[3]
Inputs		
SRWC chips @ 30% MC ($t\ a^{-1}$)	39200	31350
Fuel (Oil/Natural gas)($t\ a^{-1}$)	70	1.8
Water ($m^3\ a^{-1}$)	60	3579
Power consumption (MWh a^{-1})	1050	458
Limestone/dolomite ($t\ a^{-1}$)	154	0
Nitrogen consumption ($t\ a^{-1}$)	350	0
Outputs		
Electricity (GWh a^{-1})	40.2	25.9
Heat (GWh a^{-1}	83.9	82.3
Performance		
Heat rate (MJ kWh^{-1})	13.1	16.4
Electrical efficiency (%)	27.5	22.1
Total efficiency (%)	85	92
Emissions to air (based on 10% O2 in flue gas)		
CO2 ($t\ a^{-1}$)	0	0
CO ($t\ a^{-1}$)	36.1	118.9
NOx ($t\ a^{-1}$)	32.1	90.5
SOx ($t\ a^{-1}$)	0.6	3.36
PM ($t\ a^{-1}$)	0.9	16.8
Emissions to soil and water		
Ash ($t\ a^{-1}$)	77	138
Waste water ($m^3\ a^{-1}$)	4032	4500
Flue gas condensate ($m^3\ a^{-1}$)	2260	3500
Plant capacity (MW)	20	20
Operating hours (hrs a-1)	7000	5500

1.3 Allocation

Given that bioelectricity and bioheat are jointly produced by the CHPs, allocation was carried out in order to apportion the land use, energy use, and GHG emissions between bioelectricity and bioheat. Different methods exist to deal with allocation. However, most of these allocation methods do not consider the quality of the energy [4]. For example, 1 kWh_e seems more valuable (in energy terms) than 1kWh heat. Exergy based allocation was chosen for this study since it correctly grasps the usefulness of bioelectricity over bioheat [5]. The exergy content of bioelectricity is equal to its energy content. The exergy content of bioheat depends on its temperature relative to the surrounding environment. It can be represented via the thermal efficiency of the Carnot cycle. Table 5.S4 summarizes the parameters used to calculate the allocation factor for bioelectricity and bioheat. An energy based allocation method was carried out in the sensitivity analysis to assess the influence of the choice of allocation method in the results of our study.

Table 5.S4 Exergy-based allocation used to partition impacts between bioelectricity and bioheat. The columns from left to right denote the conversion technology, ambient temperature, steam temperature, the Carnot factor, the exergy content of electricity, the total exergy, allocation factors for bioelectricity, and bioheat.

Technology	Ambient temperature (°K)	Steam temperature (°K)	Carnot factor $\eta = (T_s-T_a)/T_s$	Annual bioheat (GWh)	Bioheat exergy (GWh)	Bio-electricity exergy (GWh)	Total exergy (GWh)	Share of bio-electricity	Share of bioheat
Gasification	288	393	0.27	83.9	22.65	40.2	62.85	0.64	0.36
Combustion	288	393	0.27	82.3	22.22	25.9	48.10	0.54	0.46

NB: the exergy content of 1kWh electricity is 1. The exergy content of heat depends on its temperature. The Carnot factor is used to calculate the allocation factor for bioelectricity and bioheat.

1.4 Energy ratio

The energy balance for bioelectricity is defined in this study as the ratio of the energy contained in 1 kWh_e divided by the fraction of the energy required for its production. Equation 1 illustrates the formula used to calculate the energy ratio (ER).

$$ER = \frac{E_{bioelectricity}}{\gamma \cdot \mathrm{E}_{input}}$$

Where $E_{bioelectricity}$ is the energy content of 1 kWh_e, E_{input} is the total fossil energy required to produce bioelectricity and bioheat, and γ is the allocation factor for bioelectricity. Note that if no bioheat was produced: $\gamma = 1$. However, since bioheat is produced simultaneously with bioelectricity: $0 < \gamma < 1$.

1.5 Reference system and emissions savings

Data on share of electricity generation by fuel types in EU in 2009 were gathered from the European Environment Agency (EEA) [6]. According to the EEA, the non-renewable fuels grid mix electricity was as follows: 58.5% nuclear, 33.8% natural gas, 7.1% coal, and 0.5% oil-fired power, whereas the fossil fuels grid mix electricity consisted of 81.6% natural gas, 17.2% coal, and 1.3% oil-fired power [6]. Using data for GHG emission factors of coal, gas, nuclear, and oil-fired power derived from the Ecoinvent database [1], we computed the GHG emission rates of the EU grid mix electricity in 2008 as indicated in Equation 2:

$$GHG_{grid\ mix} = f_n E_n + f_g E_g + f_c E_c + f_o E_o$$

Here $GHG_{grid\ mix}$ represents the GHG emissions of the EU non-renewable grid mix electricity ($gCO_2eq\ kWh_e^{-1}$); f_x is the share of electricity generation fueled by source X (%); E_x is the GHG emission factor for source X ($gCO_2eq\ kWh^{-1}$); X denotes the different fuel sources (n: nuclear; g: natural gas, c; coal; o: oil). We used the same approach to compute the GHG emissions of the EU fossil fuels grid mix electricity production in 2009. The results are summarized in Table 5.S5.

To calculate the GHG emission savings, we compared the GHG emissions of bioelectricity to those of the reference systems (non-renewable grid mix electricity) as illustrated in Equation 3. Our estimates of GHG savings include emissions from SRWC production, transport, and conversion to bioelectricity.

$$GHG\ savings\ (\%) = \frac{(GHG_{grid\ mix} - GHG_{bio})}{GHG_{grid\ mix}} * 100$$

Table 5.S5 Greenhouse gas emissions (GHG) of the EU grid mix electricity in 2009. The columns from left to right denote the generation sources, amount of electricity generated, contribution of each source to the grid mix, emission rates of each of the generation sources, and the grid mix GHG emissions.

Items	Electricity generated [6] (TWh)	Share by fuel (%)	Share by fuel excl. RES (%)	Share by fuel excl. RES & nuclear (%)	GHG emission factors [1] ($gCO_2eq\ kWh_e$)	GHG emission rates excl. RES ($gCO_2eq\ kWh_e$)	GHG emission rates excl. RES & nuclear ($gCO_2eq\ kWh_e$)
Generating sources							
Coal fired power	824.2	25.3	32.2	49.4	1020	328.4	503.8
Oil fired power	93.8	2.9	3.7	5.6	868	32.1	48.6
Natural gas power	751.2	23.1	29.3	45.0	614	179.9	276.3
Nuclear power	893.9	27.5	34.9	–	7.9	2.8	–
Renewable power	638.1	19.6	–	–	–	–	–
Other fuels	54.7	1.7					
Power transmission	–	–	–	–	–	2.5	2.5
Grid mix electricity	**3255.8**	**100**	**100**	**100**	–	**564**	**832**

Note that RES and other fuels are not considered in non-renewable grid mix electricity. RES: renewable energy sources

1.6 Land requirement

The land requirement of bioelectricity from SRWCs analysed in this study is shown in Figure 5.S2

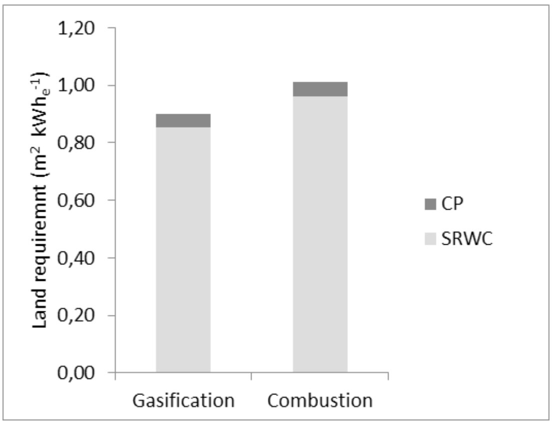

Figure 5.S2 Land requirement of bioelectricity production. CP: cuttings production; SRWC: short rotation woody crop.

1.7 Chemical composition and heating value of the SRWC chips

The chemical composition and heating value of the SRWC chips are presented in Table 5.S6.

Table 5.S6 Chemical composition and heating value of SRWC chips. The columns from left to right denote: the feedstock, chemical elements, ash content, moisture content, and high heating value of SWRC chips.

Feedstock	Elements (% db)						Ash (% db)	MC (% wb)	HHV (MJ kg^{-1})
	C*	H*	O*	N	S	Cl			
SRWC chips	47.1	6.1	44.1	0.54	0.05	0.02	2.1	50	19.45

MC: moisture content, HHV: high heating value; db: dry basis; wb: wet basis
* These values were not measured but estimated from literature.

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THE 2013 REFORMS OF THE FLEMISH RENEWABLE ELECTRICITY SUPPORT: MISSED OPPORTUNITIES

THE 2013 REFORMS OF THE FLEMISH RENEWABLE ELECTRICITY SUPPORT: MISSED OPPORTUNITIES

Abstract

Up to 2013, Flemish renewable electricity support was characterized by a lack of qualification of the various renewable supply technologies, by excess profits and by the dysfunction of the green certificate market. Major 2013 reforms introduce banding to differentiate support for various RE categories. The differentiation of renewable electricity technologies is still inadequate and the method of calculating support levels is questionable. Decreasing excess support is the main goal of the 2013 reforms, but applying German feed-in tariff rates on 18 reference technologies shows that most projects continue to receive high support. The 2013 reforms do not cure the malfunctioning of the green certificate market. The 2013 reforms increase the risks for RES-E investors, because the terms of the system can be altered by retroactive adjustment of support levels and by political intervention. Further reforms in the future are likely, decreasing the stability and reliability of the system.

Keywords tradable green certificates; quota-based incentives; policy instruments; renewable energy

Submitted as: El Kasmioui O., Verbruggen A. and Ceulemans R. (2013) *The reformed Flemish green certificate scheme: Barriers and opportunities.* Energy Policy.

List of abbreviations

BD	Banding Divisor
BF	Banding Factor
FG	Financial Gap
FIT	Feed-In Tariff
MSW	Municipal Solid Waste
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Source
RES-E	Electricity from Renewable Energy Sources
ROI	Return On Investment
SERV	Social and Economic Council of Flanders
TGC	Tradable Green Certificate
VEA	Flemish Energy Agency
WWT	Waste Water Treatment

1 Introduction

Main concerns about current energy supplies are: (i) low shares of renewable energy sources (RES) in the energy mix; (ii) negative impacts of energy use on the global carbon cycle, and consequently on the climate; (iii) increasing dependency of the European Union (EU) on energy imports (beyond 50%) from non-EU countries [1,2]. Besides effectively reducing the consumption of fossil fuels through energy efficiency measures, an increased use of RES can also mitigate the current and future atmospheric CO_2 increase and decrease the fossil fuel dependency [1]. In addition, electricity from renewable energy sources (RES-E) provides a number of politically favorable socio-economic benefits such as the increase of domestic (local) employment, the improvement of the trade balance and the increase of diversity in energy sources [3].

However, the generation costs of RES-E are still higher than the production costs of electricity from non-renewable sources, as nuclear or fossil fuels [4]. These installations have in many cases been written off and their large external costs are not reflected in the electricity price [1,5]. To encourage a widespread deployment of RES for the production of electricity and an optimal energy mix from a social point of view, active government intervention is necessary to correct market inefficiencies. Almost 120 countries have put in place various national and/or regional (financial) incentives to support the production of green electricity [6–8]. Many of these policies were frequently reformed and/or expanded since their introduction [9,10]

In this contribution we focus on the 2013 reforms of the Flemish renewable electricity incentive scheme based on tradable green certificates (TGC) that have been previously described [11–13]. The incentive scheme for combined heat and power (CHP), although regulated by the same Flemish decree, is not assessed in this study to maintain the focus on RES-E. Off-shore wind energy is also excluded, as this falls outside the jurisdiction of the Flemish authorities. The objectives of this study are: (i) to present the most important changes of the 2013 TGC reforms in Flanders; (ii) to identify the missed opportunities of the new scheme in comparison with the previous TGC scheme; and (iii) to quantify the level of support for 18 RE categories through TGC as compared to feed-in tariffs (FIT) assuming the German FIT rates. This contribution is set out as follows: section 2 describes the history of the green certificate scheme in Flanders and its impact on the renewable energy (RE) deployment. Section 3 provides an overview of the 2013 TGC reform process. Section 4 formulates and discusses critical issues about the reformed TGC system as compared to the previous system. In section 5 a simulation exercise is made comparing the Flemish scheme with the FIT scheme using the German FIT rates. The final section formulates the final conclusions.

2 Overview of RES-E policy in Flanders

In 2002 the Flemish government introduced a quota-based TGC system to support the development of RES-E. At the introduction, the Flemish authorities issued one TGC for every 1000 kWh of RES-E generated by RES-E producers, irrespective of the technology or source used [14]. There was no time limitation for obtaining TGC, i.e. these certificates were assigned as long as the RES-E unit is productive. Buyers of TGC are electricity supply companies. Every 31st of March, the latter must submit to the regulator VREG, certificates for a proportion (i.e. quota) of their electricity supplies during the previous year. Besides buying TGC, electricity suppliers may also produce RES-E themselves for which they receive TGC as well [14]. For every missing certificate a high penalty is charged, also serving as ceiling price for TGC exchanges (Figure 6.1).

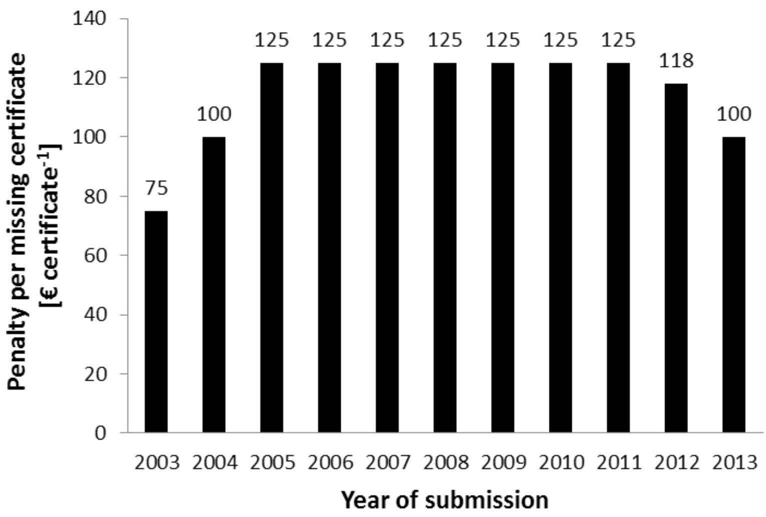

Figure 6.1 Evolution of the penalty for missing certificates at submission date (period 2003–2013). [15]

In 2004, market working was curtailed by assigning RES-E producers the right to sell TGC at a minimum price to the distribution network company in their region. The distribution network companies must pay, during a period of 10 years, a minimum price for certificates from RES-E units connected at their distribution grid and commissioned since June 8, 2004 [15]. This obligation was extended for PV as of January 1, 2006 with a payment during 20 years [16]. The obligations introduced some differentiation by technology, as the minimum support differed by RE technology used [12] (Table 6.1). Since 2004 the minimum support for the different RE technologies was changed several times, as shown in Table 6.1 and 6.2. The guaranteed minimum price and remuneration period changed most for photovoltaic (PV) power generation (Table 6.2). Electricity supply companies were not interested in buying PV TGC, because their minimum prices were higher than the penalty levels until mid-2012 (compare Figure 6.1 with Table 6.2). The high minimum support for PV in fact excluded PV certificates from TGC market activity. The obligation on distribution network companies to buy PV certificates at above TGC penalty prices corresponded to an actual FIT for PV owners.

Table 6.1 Minimum support for various RE technologies excluding PV. [15]

Technology	Minimum support during 10 years [€ certificate^{-1}]		
	Unit commissioned before Jan. 1, 2010	Unit commissioned as of Jan. 1, 2010	Unit commissioned between Jan. 1, 2012 and Dec. 31, 2012
Onshore wind energy, biomass (organic-biological substances) and biogas (organic-biological substances)	80	90	90
Organic fraction of municipal solid waste, landfill and biogas from waste water treatment	80	60	60
Biogas from fermentation of mainly agrarian flows, biogas from selected waste with composting	100	100	100–110
Hydropower, tidal and wave energy, geothermal energy	95	90	90
All other technologies for the generation of electricity from renewable energy sources	0	60	60

Table 6.2 Support for electricity generated by photovoltaic installations. [16]

Date of commissioning of the PV unit	Minimum support [€ certificate^{-1}]	Duration of the support guarantee [years]
July 2002 – December 2005	150*	10*
January 2006 – December 2009	450	20
January 2010 – December 2010	350	
January – June 2011	330	
July - September 2011	300	
October – December 2011	270	
January – March 2012	250	
April – June 2012	230	
July 2012	210	
August – December 2012	90	10

* In addition to the obligation on Flemish distribution network companies to buy certificates from PV installations commissioned as of January 1, 2006, the Belgian transmission system operator (ELIA) was obliged to buy certificates from PV installations commissioned after July 1, 2003 and before August 1, 2012 for a period of 10 years at 150 € certificate^{-1} [15,16]. However, one certificate can only be sold once making the second option obsolete as of 2006, given the lower minimum price.

In addition to revenues from TGC sales at (posted or negotiated) variable prices to power suppliers or at minimum prices to distribution network companies, RES-E producers earn revenues from selling (physical) electricity to the grid, or from lowering their electricity bill in case of own RES-E use. Next to the support of RES-E a diversity of (in)direct measure at different government levels (federal, regional and municipal) exist(ed) to support these technologies. However, a full overview of these support measure is beyond the scope of the current study.

Figure 6.2a shows the growth in RES-E generation over the period 2002–2012, reflected by the amount of issued TGC in Flanders. Following the introduction of RE support in 2002, the share of RES-E in the electricity supply increased from 0.6% in 2002 to 1.1% in 2004 [17]. Since 2004, minimum support is guaranteed and RES-E output is growing faster, to achieve a 7.5% share of supplied electricity by 2011. The impact of introducing high support levels is most explicit for PV, increasing in output from 1.4 GWh in 2006 to 1700 GWh in 2012 [18]. The high support, combined with significant decline in investment per kW_p, brought paybacks of about five years within reach of well-designed systems, with guaranteed significant profits during the remainder of the 20-year support period.

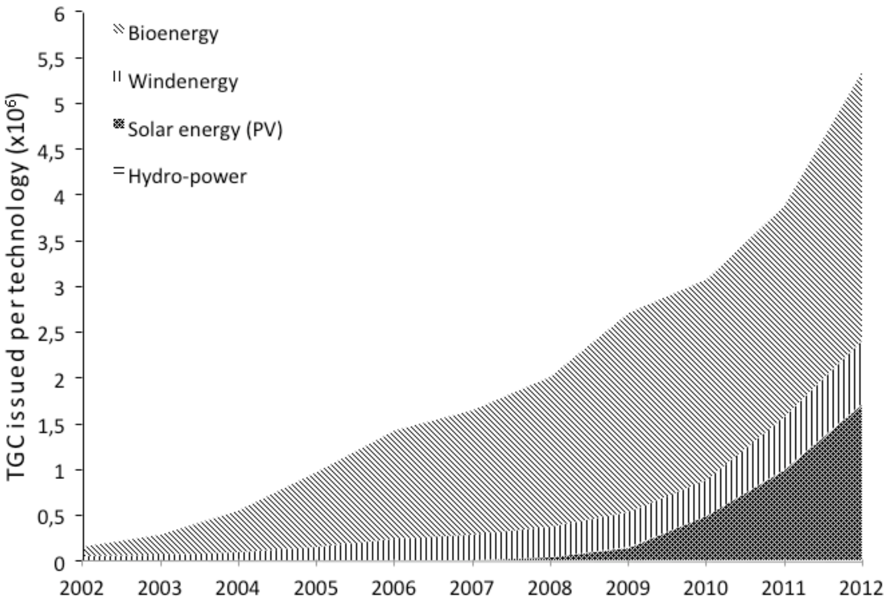

Figure 6.2a Issued TGC by technology in Flanders from 2002 to 2012 - general overview. [18]

Figure 6.2b also reveals a high growth in assigned certificates for bioenergy, from 104000 in 2002 to almost 3 million in 2012, reflecting a power output of 0.1 TWh to almost 3 TWh yearly rewarded by certificate assignments. Biomass from separately collected or sorted organic waste and biomass from agriculture and forestry contributed most to this growth with a 75% share in the bioenergy mix in 2012 (Figure 6.2b). The steep increase in 2005–2006 in the share of biomass from agriculture and forestry is attributed to the co-firing biomass in (existing) coal power plants. The surge of biomass from separately collected or sorted organic waste is due to the eligibility of two existing biowaste plants (81 MW and 55.7 MW) and by commissioning four new plants in the period 2004–2006 (installed capacity of 69.8 MW), followed by six new plants in 2009–2011 with a joint installed capacity of 110 MW [19]. The organic-biological fraction of municipal solid waste (MSW) can only qualify for TGC as of April 2004, explaining the appearance of MSW incineration in 2004, while this capacity was already available earlier [12]. The considerable decrease in the share of biomass from agriculture and forestry in 2010 is because not all electricity generated from co-firing this biomass is eligible for certificates as of January 1, 2010.

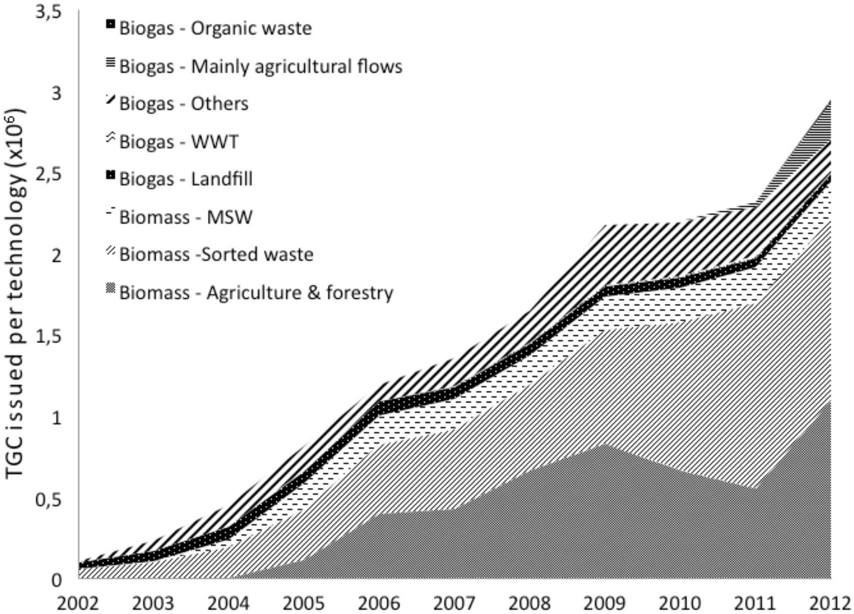

Figure 6.2b Issued TGC by technology in Flanders from 2002 to 2012 - focus on bioenergy fraction (WWT: waste water treatment; MSW: municipal solid waste). [18]

3 Reform of the green certificate scheme

The Flemish green certificate system experienced several modifications since January 1, 2002. The changes insufficiently addressed a major concern of the support system, i.e. the high excess profits due to the missing qualification of RES-E technologies [11–13,20]. RES-E encompasses various technologies with specific attributes and in different phases of maturity, requiring a different support [13]. As all RES-E plants, regardless of their attributes, received one certificate per MWh production, some technologies benefited by free riding (e.g. co-firing of biomass in old coal power plants), while other more innovative technologies did not pass the hurdle rate (e.g. innovative biomass conversion technologies, such as gasification technologies).

From January 1, 2013 onwards, banding factors (BFs) are applied on the issued certificates. RES-E plants are classified in 18 categories depending on the type of the RE source, technology and capacity of the plant. The categories are assigned BFs, based on the gap between estimated profitability of reference plants by category and preset returns on investment (ROI). For PV plants with a peak capacity above 750 kW_p, wind energy turbines larger than 4 MW and other RES-E units with capacities beyond 20 MW individual and specific plant BFs are assessed when RES-E plant owners apply for support [21].
The ROI calculations of RES-E plants assume ownership of the technology by either private households (PV < 10 kW_p) or by companies (all other RES-E investments). The various owners are assumed being submitted to different financial conditions and rules (e.g. tax regimes) that affect their final net return on their investments, with varying demands on the hurdle rates. The "financial gap" is estimated on this basis as a yearly quantity of money needed as a subsidy for guaranteeing the preset ROI. The subsidy is expressed in euro per MWh RES-E produced by the project.
The applied formula is (Eq. 1) [22]:

$$\mathrm{NPV}\left(\mathrm{FG}\right) \equiv -\mathrm{I} + \sum_{t=0}^{T_b+T_c} \frac{OCF_t\left(FG\right)}{\left(1+r\right)^t} = 0$$

with FG = the financial gap, I = the amount of the total investment, T_b = the policy period, T_c = the construction period, OCF_t = the operational cash flow in year t and r = the desired return on investment (ROI). In 2003, this calculation method was described by de Noord and van Sambeek [23] of the Energy Research Centre of the Netherlands. Although the formula appears relatively simple at first glance, the effective calculation of the financial gap is opaque due to the large number of parameters taken into account to calculate the operational cash flow over the considered period.
For implementing the regulation, a large number of parameters for the various reference technologies have to be fixed. Some examples of these parameters are: electrical efficiency, electricity generated, full load hours of the RES-E plant, share of RES-E in electricity used on site, the owner's interest rate on bank loans, the

owner's debt/equity ratio, the owner's taxation rate, etc. (see Table 6.S1 for the full list). Assessed financial gaps (FG) in € MWh^{-1} RES-E are divided by a common banding divisor (BD) of € 97 certificate^{-1}, to obtain the category specific BF (BF = FG/BD). The BF is the number of certificates attributed to 1 MWh RES-E of a specific category. The BF cannot be higher than 1 for plants commissioned in 2013, and can never be higher than 1.25 [22,24]. The BD is set at € 97 certificate^{-1} as the Flemish authorities assume that the average 'market' price will be somewhat lower than the penalty, which is stipulated at € 100 per missing certificate as of March 31, 2013 (Figure 6.1). BFs by category are re-calculated at least once a year (twice a year for PV) by the Flemish Energy Agency (VEA) to incorporate price evolutions. If the difference between the initial BF and the actualized BF is larger than 2%, the latter is applied both for new installations and for installations that were commissioned earlier.

We illustrate the 2013 reforms of the support scheme with a practical example of solid biomass-fired conversion plants. Up to December 31, 2012 irrespective of the installed capacity, such plants received one certificate for every MWh of electricity generated. Since January 1, 2013 a solid biomass-fired plant with an installed capacity up to 20 MW receives 1 certificate for every 1.02 MWh of electricity generated (BF for solid biomass $\leq$ 20 MW: 0.98). A plant larger than 20 MW must apply for a project-specific BF to be eligible for TGC support.

4 Critical assessment

The poor preparation of the reform of the green certificate system has given rise to missed opportunities [25]. This section identifies items of concern and missed opportunities (Table 6.3).

Table 6.3 Items of concern about Flemish RES-E support before and after January 1, 2013.

Items of concern	TGC scheme up to Dec. 31, 2012	Reformed TGC scheme since Jan. 1, 2013
Parameters applied in calculating specific support levels	Not applicable	Large number of parameters, including a number of company-specific parameters (see Table 6.S1)
Qualification	Poor differentiation in minimum support; no qualification of RES-E technologies on their merits. Exclusion of (expensive) less mature, innovative technologies	Differentiation based on RE technology and unit capacity. Limited qualification for biogas and biomass technologies. Exclusion of (expensive) less mature, innovative technologies (BF$\leq$ 1)
Excess profits	High windfall profits for plants with marginal costs far lower than TGC prices and by slow adjustment of PV support levels	Limitation of windfall profits by technological differentiation and introduction of a project specific approach for the largest units
Investment security	Financial risk mainly due to price volatility on the electricity and TGC markets. Guaranteed minimum support offers safety valve for investors	Price volatility on the markets plus additional financial risks by uncertainty about future BF values depending on annually re-calculated financial gaps. Minimum support also dependent on BF
Market functioning	Poor functioning of the TGC market	No adequate solutions offered in reformed system
Long-term vision	No consistency and no long-term vision	No consistency and no long-term vision

4.1 Parameters for calculation

The parameters and spreadsheet used for calculating the financial gaps of the RE categories are made publicly available to increase transparency and investors' confidence in the reformed TGC scheme. Next to general parameters also company specific parameters, such as company tax rates and investment tax reductions, are included (see Table 6.S1). The inclusion of company tax rates in calculating the financial gap causes potentially considerable errors, as such rates vary significantly from the official Belgian company taxation rate of 33.99% assumed in the calculations [26]. Identifying effectively imposed profit-related taxes requires individual and detailed business analysis of each investment, entailing the production of annual accounts. Such an approach is practically not feasible.

The inclusion of the federal investment tax reduction, allowed for investments in RES-E, also depends on the imposed tax rate, thus increasing the aforementioned error. This triggers the discussion whether and how to include non-TGC support. Flemish farmers obtain a 28% investment subsidy on installations using RES, e.g. in cogeneration units [27].

Pre-tax calculations, excluding company-specific parameters, correspond better to a cost-effective and fair incentive scheme. A calculation of the levelized cost of electricity (LC), following Eq. 2, taking into account the investment and operating costs, as suggested by the IPCC [1], is to be preferred over the complicated financial gap calculations described in section 3 (Eq. 2):

$$LC = \frac{\sum_{t=0}^{T_b} \frac{\left[I_t + O_t + F_t\right]}{\left[1+r\right]^t}}{\sum_{t=0}^{T_b} \frac{\left[E_t\right]}{\left[1+r\right]^t}}$$

with I_t = investment costs in the year t; O_t = operation costs in the year t; F_t = fuel expenditures in the year t; E_t = electricity generation in the year t; r = discount rate or ROI and T_b = policy period.

4.2 Qualification and excess profits

The 2013 reforms of the green certificate system aim at higher cost-effectiveness of the TGC by harmonizing support levels on financial gaps. By fixing support levels at generation costs, windfall profits from low-cost technologies should be avoided. The 2013 reforms differentiate support by classifying RES-E technologies in 18 categories. The identification of the categories seems rather arbitrary. Some categories include conversion technologies with diverging attributes and capacities, e.g. combustion of solid biomass with a capacity up to 20 MW has been put in one category. But a 100 kW installation significantly differs in economies of scale and costs from a 20 MW installation. Only for biogas technologies additional differentiation by unit capacity (0-5 MW and 5-20 MW) and by source (landfill, sewage, etc.) is applied. Fine sub-categorization, as in the German Renewable Energy Sources Act (EEG), is lacking, causing sub-optimal incentives. Fine-tuning of the regulatory treatment based on the attributes of every RES-E 'source–technology' combination would allow classification of the various combinations in diverse groups with adapted incentive levels (BFs in the Flemish case [5]. In addition to the unit capacity and the RE-category, elements such the inputs/fuels used for biomass or biogas, and the technology deployed (conventional vs. innovative, e.g Organic Rankine Cycle (ORC), etc.) should be taken into account [28].

RES-E incentive policies are designed to support the deployment of RES-E technologies, but could also help in charging or remunerating external costs or benefits. Cost assessments of the ecological impact of the various RES-E 'source-technology' pathways may contribute to an improved qualification of biomass or biogas sources. Such assessments may suggest slight support differences for plants within a given RES-E category. E.g., the European Commission's Costs Assessment for Sustainable Energy Systems (CASES) reveals large differences in external costs of biomass combustion depending on the source used (straw versus wood-chips) [29].

The 2013 reform also provides that the Flemish government can – by decree – limit the value of the BF, regardless of the financial gap calculations [24]. Arbitrarily limiting BFs to a maximum of 1 (during 2013) and of 1.25 (during the following years), confine the expenses of the support system by only supporting less expensive and in the short run most cost-efficient RES-E technologies. Long-term innovation potential, or local social-economic benefits and environmental benefits, may justify higher initial costs, and thus BF higher than 1 and 1.25. Innovative technologies are generally expensive in their development phase, but become economically feasible once they pass to maturity [30,31]. Decreasing unit costs by learning is demonstrated by PV, which would be profitable without government support in Flanders if no additional grid compensation fees were charged for PV. A myopic focus on short-term cost-effectiveness lacks a long-term vision on how the various RES-E technologies should develop in order to contribute to an overall stable and reliable supply of electricity.

4.3 Investment security and market functioning

Flemish politicians [35] argue the 2013 reforms intend to grant security to investors by providing sufficient support to make the investment in a specific technology profitable. Quota systems are praised for their ability to achieve certain pre-defined goals with respect to the future share of RES-E in the energy mix [36]. But they provide less certainty for the investors due to the unknown level of future incentives, as this depends on the TGC prices [3]. In 2004, Flemish legislators decreased the volatility of TGC prices by guaranteeing minimum prices as safety net for RES-E investors (Section 2). This minimum support also reduces the downward pressure on TGC prices in years with excess supply [36]. The 2013 reforms further reduce the volatility of TGC prices by limiting their range through an increase of the minimum price to € 93 certificate^{-1} and a decrease of the penalty to € 100 certificate^{-1}.

However, measures to mitigate excess profits decrease both the certainty for (future) investors and the confidence regarding the future of the TGC system. Examples of such measures include the possibility to yearly adapt the BF for both new and ongoing projects based on new financial gap calculations (Section 3), and the retro-active limitation of TGC assignment to a period of 10 years for projects commissioned before the reforms (i.e. before January 1, 2013).

The lack of a functional TGC market further decreases the investment security, while increasing the cost of the support scheme. Since the start of the TGC scheme the certificates have been exchanged on a bilateral basis with mostly long-term contracts between RES-E producers and electricity suppliers. Only a negligible amount of certificates was traded on BELPEX's special Green Certificate Exchange (GCE) [37]. Since its launch in 2009, BELPEX organized 11 trading days with five days without transactions (Figure 6.3). As of 2011, BELPEX did not organize trading days, expecting very few transactions due to the market circumstances in the TGC scheme [38]. Verbruggen and Lauber [5] and Haas et al. [9] point to the difficulty – if not impossibility – to establish a competitive TGC market on top of a non-competitive conventional electricity market.

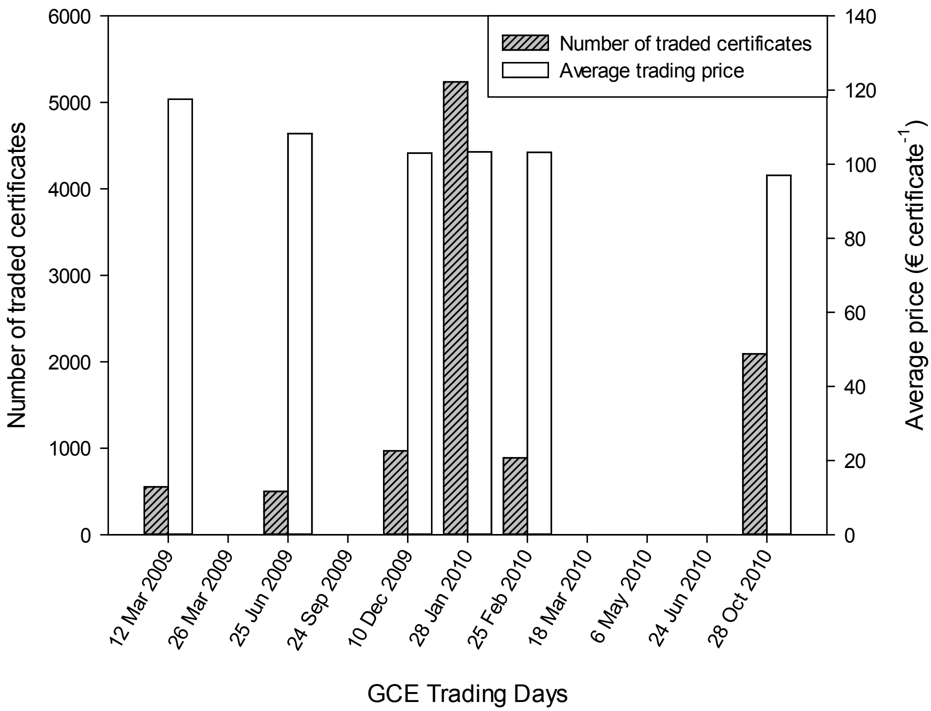

Figure 6.3 Flemish tradable green certificates traded at BELPEX Green Certificate Exchange (GCE) during the 11 trading days in 2009 and 2010 (an empty spot above a date means no certificates were traded during the day). Both quantity and price are shown. [37]

The surplus of available TGC compared to submitted TGC adds to the market dysfunction. Since 2006, the surplus has accumulated to 2.1 million certificates on March 31, 2012, i.e. 71% more available certificates than submitted certificates that day (Figure 6.4) [39]. The surplus results (i) from the initial success of the TGC scheme, (ii) from qualifying the organic-biological fraction of municipal solid waste for TGC since April 2004, and (iii) from the inability of the Flemish authorities to monitor and control the certificate market. Before 2007 there was an automatic coupling between produced certificates and the certificates to be submitted (=quota) in the same year, explaining the steep increase of excess since the decoupling [13,40].

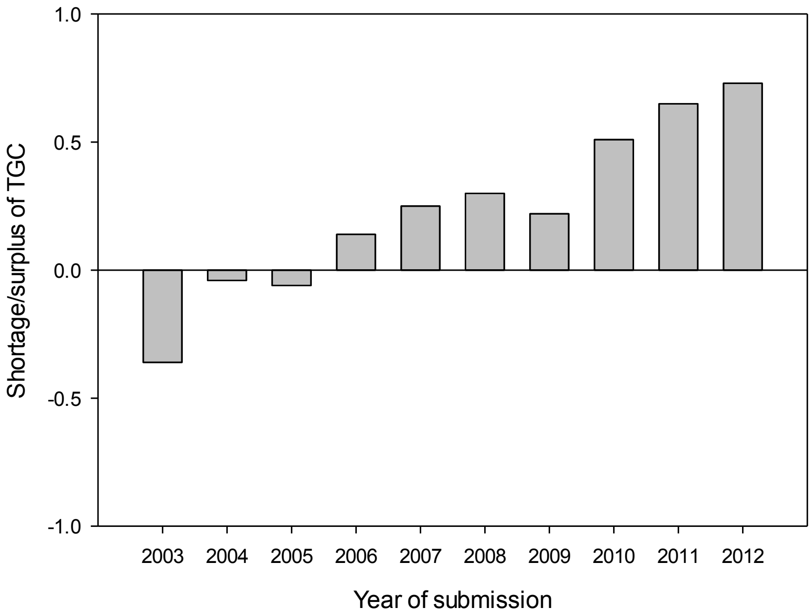

Figure 6.4 Flanders (2003–2012): TGC shortage or surplus at submission date March 31, expressed as percentage (= [available, accumulated TGC] / [TGC to be submitted] – 1) (Abbreviations have been explained in the list of abbreviations). [39]

Higher risks to recover investments due to the volatile TGC market, combined with the uncertainty about the future evolution of BF and electricity sales prices, lead to an additional risk premium increasing the support costs of the transition to RES-E [41,42]. Section 5 shows that the support provided by the Flemish reformed TGC scheme is still higher than the support of the German FIT scheme. This is in line with the findings of studies published earlier [20,43]. Several studies have indeed shown that countries which adopted the FIT scheme generally provide less support while demonstrating higher deployment rates of RES-E [41,44–46]. A higher security level of investments decreases the costs of the transition to RES-E as it provides a downward pressure on the price of borrowing, it reduces the request for high ROIs and it stimulates technological development reducing costs as well [28].

5 Quantitative comparison with the German feed-in tariff scheme

FIT are evaluated as the most efficient and most effective support system to stimulate the deployment of RES-E [7,44,47]. This section compares the RES-E support by the 2013 reformed Flemish TGC system with the support provided by the German FIT scheme, since Germany counts as a benchmark for RES-E policies [41,46]. The comparison is based on assessed revenues for RES-E generators through the sales of TGC and of physical electricity on the one hand, and through FIT on the other hand. As sales electricity price is adopted € 50.6 MWh^{-1} for all RES-E categories, based on the ENDEX year-ahead price in 2012 [33]. We assume constant electricity prices over the studied time period, in contrast to the financial gap calculations by VEA that include yearly price increases of 2%. Our assumption is based on electricity futures at the ENDEX market; the futures reveal price stabilization with even a decrease in Belgium [48].

For each of the Flemish 18 RES-E categories, VEA [21,33,34] defined one reference unit via an elaborated list of parameters (Table 6.4). On the different reference units, we apply German FIT rates dependent on deployed RES-E technology and rated capacity, using the methodology exemplified in the German Renewable Energy Source Act [49]. The latest information, in particular about the modified FIT for solar energy, from the website of the German Federal Network Agency [50] is included. We apply only base tariffs for the different technologies, as Flanders does not differentiate beyond the subdivision in 18 RES-E categories. Table 6.S2 provides an overview of the base FIT rates guaranteed by the German support scheme. Details about the statutory requirements or potential FIT increases or reductions, from bonuses based on e.g. substance class of the feedstock used for biomass technologies or the processing of biogas for feeding into established natural gas networks [49,51] are not included.

Table 6.4 Assessed revenues obtained by RE producers through the (Flemish) TGC scheme and (German) FIT scheme, based on the listed parameters [Acronyms and abbreviations explained in Table 6.S1 and list of abbreviations]. [21,33,34,49,50].

Categories	U [kW]	VU [h]	ηel [%]	Electricity generated [MWh]	BF	BF (max.)	EV_{EL} [%]	EV_{GSC} [%]
PV								
PV ≤ 10 kW	5	850	100	4.25	0.23	0.23	0.0	0.0
PV ≤ 250 kW	125	850	100	106	0.63	0.63	0.0	0.0
PV ≤ 750 kW	400	850	100	340	0.49	0.49	0.0	0.0
Wind								
Wind ≤ 4 MW	2300	2000	100	4600	0.83	0.80	0.0	0.0
Biogas ≤ 5 MW								
Agricultural	1900	7000	39	5187	1.59	1.00	10.0	0.4
Biowaste	1300	7200	39	3650	2.12	1.00	22.0	0.0
Landfill	500	4600	35	805	0.20	0.20	2.0	2.0
Sewage	290	3000	32	278	0.21	0.21	2.0	2.0
Other	2000	7000	39	5460	1.66	1.00	10.0	0.0
Biogas ≤ 20 MW								
Agricultural	7000	7000	39	19110	1.24	1.00	10.0	2.4
Biowaste	7000	7200	39	19656	1.48	1.00	22.0	2.0
Landfill	5500	4600	35	8855	0.00	0.00	2.0	2.0
Sewage	5500	3000	32	5280	0.00	0.00	2.0	2.0
Other	7000	7000	39	19110	1.33	1.00	10.0	2.0
Biomass ≤ 20 MW								
Solid	10000	7900	26	20540	0.98	0.98	2.0	2.0
Liquid	800	3000	40	960	1.92	1.00	1.2	10.0
Biowaste	10000	7900	26	20540	0.83	0.83	2.0	2.0
Municipal Solid Waste	7167	7800	20	11181	-0.08	0.00	2.0	54.2

ZA_{EL} [%]	$P_{EL,ZA}$ [€ kWh^{-1}]	r [% y^{-1}]	Rated capacity [kW]	Average FIT [€ kWh^{-1}]	Total revenues TGC [k€]	Total revenues FIT [k€]
100	0.217	5	0.49	0.170	12	9
65	0.151	5	12.13	0.169	218	223
65	0.132	5	38.81	0.151	599	639
0	n.r.	8	525	0.088	5215	3974
0	0.111	12	1518	0.114	4208	3973
30	0.111	12	1068	0.146	2958	3113
0	0.187	12	263	0.085	378	499
90	0.111	12	99	0.067	243	136
10	0.111	12	1598	0.114	4661	4171
0	0.104	12	5594	0.104	15321	13395
30	0.104	12	5753	0.139	15507	15907
0	0.104	12	2888	0.063	3284	4059
90	0.104	12	1884	0.060	3796	2333
10	0.104	12	5594	0.104	16037	13395
40	0.083	12	9018	0.087	19762	13081
40	0.111	12	274	0.131	978	930
30	0.083	12	9018	0.087	17667	13081
30	0.083	10	14692	0.000	5630	5630

First, the revenues are calculated for one operational year during the support period. This shows the difference in revenues between the two support schemes without taking into account the difference in support period. Then, the one-year revenues are extrapolated over 20 years to observe the impact of the support period on the total revenues. German FIT are guaranteed for 20 years, whereas Flemish TGC are only issued for 15 years after commissioning for wind and PV, and only for 10 years after commissioning for other technologies. After this period, the only revenues that RES-E generators receive in the TGC scheme are revenues from the sales of physical electricity.

The annual monetary values were discounted using the return on investment (ROI) reported by the VEA for the various categories (r in Table 6.4). By using different discount rates for the different RE categories we incorporate the assumed differences in risk associated with the various investments. The TGC price is set at € 93 $certificate^{-1}$, being the minimum support guaranteed by the Flemish system.

For 11 out of the 18 reference units the TGC scheme (+ the sales of electricity) shows higher revenues than the FIT scheme, considered both over a period of one year and over a period of 20 years (Figure 6.5). Three out of the 18 reference units (i.e. PV units of 125 kW_p, biowaste fueled biogas installations of 1.3 MW and 7 MW) receive higher revenues from TGC during one year, but there is a reversal in favor of FIT when revenues are discounted over 20 years. The difference between revenues through the TGC and FIT schemes for the three technologies is rather small (max. 5%). Three reference units are insufficiently supported through the TGC scheme as compared to the FIT scheme, in particular RES-E generated from landfill gas which is subdivided in two categories based on the plant capacity. The BF of biogas units with a capacity up to 5 MW was set at 0.2. The BF is 0 for biogas units with a capacity between 5 and 20 MW, excluding the units from TGC support. This causes the large difference (up to 32%) between the assessed TGC and FIT revenues.

Electricity from the organic-biological fraction of MSW does not receive FIT in Germany [51]. Since 2013, it does no longer receive TGC in Flanders because the financial gap calculations show MSW electricity generation is profitable without government support [21].

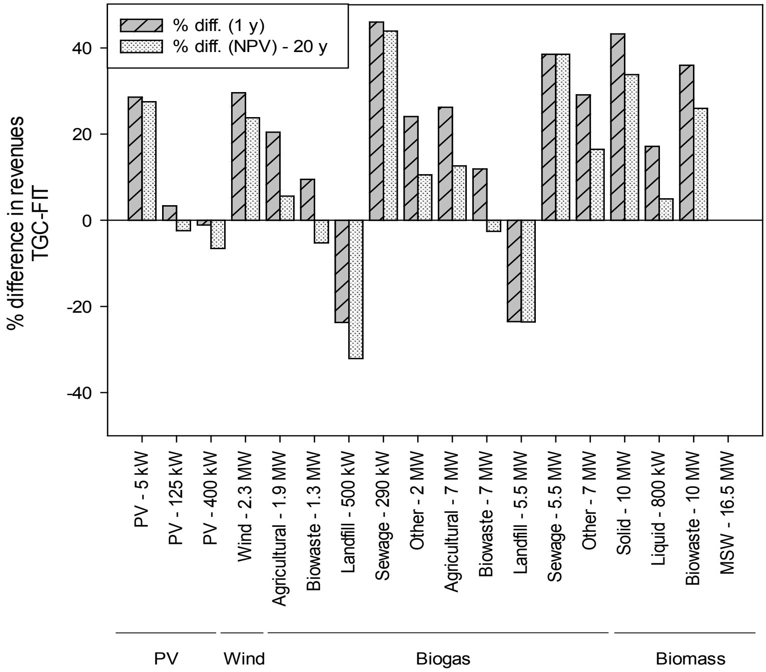

Figure 6.5 Percentage difference between the revenues by 2013 Flemish TGC and the revenues by 2013 German FIT for 18 RES-E reference units (revenues: once over one year, once net present value discounted over 20 years) – Positive value: higher revenues through TGC; negative value: higher revenues through FIT

6 Conclusion

The article assesses whether the 2013 reforms of the Flemish TGC scheme remedies important shortcomings of the scheme, in casu: missing qualification of RES-E technologies, excess profits and dysfunction of the TGC market. Technology bands introduce differentiation of RES-E, but fail to fully qualify RES-E by taking into account all relevant attributes of the various 'source-technology' combinations. A fine-tuning of the support, as demonstrated by the German FIT scheme, is still far away. The total cost of the support system is reduced by ceiling the BF to 1.0 regardless of the results of the financial gap calculations. This continues to exclude more expensive, but possible promising RES-E technologies, from the necessary support. The Flemish authorities believed in the establishment of a competitive artificial TGC market on top of a non-competitive electricity market. However, no functional

TGC market was successfully created. With the large surplus of certificates and with the dominant positions of a limited number of actors in the power sector, the future for a TGC market does not look bright. The thoroughly reformed TGC scheme does not offers a solution for this issue.
The 2013 reforms increase the risks for RES-E investors. Politicians want to reduce the bill of the TGC system, with a focus on mitigating excess profits. By excluding medium to large RES-E units from the predefined RE categories, investors are required to file an application for a project-specific BF, to find out whether their RES-E projects will receive any support. In most cases the support is necessary to obtain funding from shareholders and financial institutions. The retroactive limitation of TGC eligibility to 10 years for units commissioned before the reforms further decreased the confidence of investors.
Until 2012, the Flemish TGC scheme was characterized by high excess profits due to the lack of qualification of the technologies and sources, and due to slow adjustment of PV support levels, when required solar panel investment declined. Our simulation exercise comparing the revenues for 18 RES-E reference units through the 2013 Flemish system with the revenues through the German FIT scheme confirms excess profits. This comparison shows that in most cases (11 out of 18 reference units) the support provided by the Flemish TGC is still higher than by applying German FIT rates. This may confirm earlier findings that higher support is required to compensate for lower investment security under TGC schemes.
The 2013 reforms will presumably not be the last, since the share of green electricity in the total electricity production in Flanders is still limited, and the Flemish support scheme can be further improved.

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Annex: Supplementary Information

Table 6.S1 Parameters used by the Flemish Energy Agency (VEA) for calculating financial gaps. [22]

U	The electrical capacity of the unit	[kW_e]
η_{el}	The net electrical efficiency of the unit	[%]
EV_{EL}	Internal use of electricity by the unit, to determine the net green electricity production (share)	[%]
EV_{TGC}	Share of the gross green electricity production not qualified for TGCs	[%]
K_i	Specific overnight capital investment per unit of power	[€ kW_e^{-1}]
r	The desired return on the total investment (ROI)	[%]
E	Equity capital share in the total investment	[%]
r_d	The interest rate on the bank loan	[%]
T_b	The policy period	[year]
T_a	The depreciation period	[year]
T_c	The construction period	[year]
T_r	The period of the bank loan	[year]
i	The part of the investment eligible for investment allowance	[%]
IAP	The percentage of the investment tax reduction	[%]
VU	The average annual full load hours	[h]
ZA_{EL}	The use of electricity for own consumption (share)	[%]
$P_{EL,ZA}$	The avoided cost of electricity in case of own consumption (year 0)	[€ kWh^{-1}]
$P_{EL,ZA,t}$	The avoided cost of electricity in case of own consumption in year t, before actualization	[€ kWh^{-1}]
$P_{EL,V}$	The sales market value of electricity in year 0	[€ kWh^{-1}]
$P_{EL,V,t}$	The sales market value of electricity in year t, before actualization	[€ kWh^{-1}]

P_{IN}	The cost for the fed-in electricity in year o (feed-in tariff)	[€ kWh^{-1}]
$P_{IN,t}$	The cost for the fed-in electricity in year t, before actualization (feed-in tariff)	[€ kWh^{-1}]
P_{TVB}	The market value excluding taxes, levies and avoided grid costs of the avoided primary fuel for the same quantity of useful heat in year o	[€ kWh^{-1}]
$i_{EL,ZA}$	The expected average yearly change of the avoided costs of electricity for own consumption	[%]
$i_{EL,V}$	The expected average yearly change of the sales market value of electricity	[%]
i_{PBW}	The expected average yearly change of the market value of the avoided primary fuel for the same quantity of useful heat	[%]
I_V	The discount value of the replacement investments per power unit in year o	[€ kW_e^{-1}]
K_V	The fixed costs per power unit year o	[€ kW_e^{-1}]
K_{Var}	The variable costs per unit of electricity generated in year o	[€ kWh^{-1}]
i_{OK}	The expected average yearly change of the market value of the operational costs	[%]
P_B	The price of fuel in year o, including financing costs for the purchase of fuel	[€ kWh^{-1}]
i_B	The expected average yearly change of the market value of the fuel	[%]
M_{IS}	The quantity (mass) of incoming material on a yearly base	[ton]
PO_{IS}	The costs or revenues from the incoming material per ton in year o	[€ ton^{-1}]
i_{IS}	The expected average yearly change of the market value of the incoming material	[%]
M_{US}	The quantity (mass) of outgoing material on a yearly base	[ton]
PO_{US}	The costs or revenues from the outgoing material per ton in year o	[€ ton^{-1}]
i_{US}	The expected average yearly change of the market value of the outgoing material	[%]
b	The corporate tax rate	[%]

Table 6.S2 Feed-in tariff rates for various RE technologies applicable for installations commissioned on January 1, 2013. [49–50]

German FIT levels (as of January 1, 2013)	€ kWh^{-1}
PV	
≤ 10 kW	0.1702
10 kW - 40 kW	0.1614
40 kW - 1 MW	0.1440
1 MW - 10 MW	0.1178
Wind energy	
Base tariff	0.0480
Initial tariff for 5 years	0.0880
Biogas and biomass units	
≤ 150 kW	0.1401
150 kW - 500 kW	0.1205
500 kW - 5 MW	0.1078
5MW - 20 MW	0.0588
Biowaste fermentation	
≤ 500 kW	0.1568
500 kW - 20 MW	0.1372
Small manure digesters	
≤ 75 kW	0.2450
Landfill gas	
≤ 500 kW	0.0847
500 kW - 5 MW	0.0580
Sewage gas	
≤ 500 kW	0.0669
500 kW - 5 MW	0.0580

GENERAL DISCUSSION AND CONCLUSIONS

GENERAL DISCUSSION AND CONCLUSIONS

Our society is highly dependent on energy services to meet our basic human needs and to serve productive processes. Current global energy supply is for approximately 80% fossil fuel-based (coal, oil and natural gas) and is widely considered to be unsustainable. Although the stocks of fossil fuels are a point of debate, other elements such as the increasing dependency on politically unstable regions for our energy supply and the high contributions of fossil fuel combustion to anthropogenic greenhouse gas (GHG) emissions, and thus to climate change, are generally recognized.

To decrease this dependency of our fossil energy supply and to mitigate these harmful impacts, the transition to renewable energy sources in combination with improved energy efficiency is indispensable. Biomass can significantly contribute to the transition to a more sustainable energy mix given its substantial growth potential [1]. Moreover, biomass is a versatile energy source as it is the only renewable energy source that can substitute for fossil fuels in all forms – heat, electricity, and liquid and gaseous fuels. In addition, bioenergy can be produced from a variety of biomass feedstock, from organic waste streams over forest residues to annual and perennial crops, grown specifically for energy production. The latter, in particular short rotation woody crops (SRWCs), such as poplar and willow, will play a major role in the supply of biomass feedstock. Although estimates vary widely, dedicated energy crops are attributed a high potential within the future bioenergy supplies [1,2].

Uncertainty regarding the financial profitability and controversy concerning the environmental impact of SRWCs for bioenergy, however, hamper the large deployment of these dedicated energy crops. Therefore, the aim of this dissertation was to investigate the financial feasibility and the energetic-environmental performance of SRWCs and to have a closer look at government policies supporting electricity from renewable energy sources (RES-E) in Flanders. In this discussion it is made clear that the combination of literature and experimental data produced a set of answers that are internally consistent, and that provide new insights into the major contributors to the financial, greenhouse gas (GHG) and energy balance of SRWCs. Additionally, the need for a stable support scheme, not only for SRWCs and biomass, but also for other renewable energy sources is discussed and underpinned.

The first major result is that SRWCs for bioenergy are not feasible from a financial point of view in almost all studied regions, without government support. Section 1 discusses the results with regard to the financial performance of SRWCs presented in this dissertation and provides more extensive framing of these results through a comparison with other energy crops and agricultural crops. The second main conclusion is that bioenergy from SRWCs provides GHG and energy benefits as compared to the non-renewable energy baseline, both in the long- and the short-term, despite the substantial variability in numerical results between studies. Section 2 discusses and explains the (wide) ranges found for the GHG and energy balance of SRWCs and integrates the values calculated for the POPFULL plantation in this discussion. The third and final conclusion is that the frequent adaptations of the (required) government support for bioenergy, and other renewable energy source, hamper and slow down the widespread deployment of RES-E technologies. This expansion towards policy analysis is made in section 3.

1 Financial feasibility of SRWCs for bioenergy

The financial viability of the cultivation SRWCs for bioenergy depends on the competitive advantage of SRWCs production compared to other land uses (in particular for agricultural crops) and other fuels. Therefore, a financial feasibility study should not only calculate the feedstock production costs, but also the overall profitability of the SRWC culture. Chapter 2 has shown that the levelized costs (LC) methodology is the only correct way to calculate the production costs of SRWCs, given their perennial nature. The overall profitability of the cultivation of SRWCs should be calculated using the traditional net present value (NPV) method. However, if one aims at a comparison with annual (agricultural) crops the equivalent annual value (EAV) method should be adopted, which is an extension of the NPV method as it annualizes the calculated NPV.

The compilation and analysis of data regarding the production costs and financial feasibility of SRWCs in various regions around the globe revealed large differences in the reported production costs, ranging from 0.8 to 5 € GJ^{-1}. These results are in line with the findings of de Wit et al. [3] reporting costs of 5.5 € GJ^{-1} for poplar in Italy and 4.4 € GJ^{-1} for willow in Sweden and of van Dam et al. [4] reporting costs between 1 and 4.5 € GJ^{-1} for the production of willow in Central and Eastern European countries. This wide range can not only be explained by differences in cultivation techniques (rotation length, type and rate of fertilizers/herbicides) and (assumed) yield. The wide range is mainly driven by differences in the calculation methodology (variable versus full cost approach), and differences in costs of exogenous factors, such as labor, fuel, and land. These exogenous factors have emphasized the importance of geographical boundaries, since the previously mentioned costs differ largely across regions complicating interregional comparison. Lack of data, omission of important variables (e.g. interest rate) and difference in system boundaries further hampered meaningful comparison. This study also revealed an urgent need for more operational field data to allow a detailed assessment of the profitability of growing SRWCs for bioenergy under different conditions.

To assess the profitability of SRWCs a detailed cash-flow model, POPFINUA, was developed in this dissertation (Chapter 3). The high level of detail and the ability to modify all relevant parameters to visualize the impact of the modification on the production costs and on the profitability of a SRWC plantation are the main novelties and improvements of the POPFINUA model as compared to other financial valuation models for SRWCs [5,6]. Additionally, the model displays a large flexibility in data requirements, since the user can opt to provide detailed data on cost items (e.g. machinery costs including depreciation, fuel use, operating rate, etc.) or opt to provide costs per hectare for cost categories for which no detailed data are available.

Table 7.1 Baseline values (net present value (NPV), equivalent annual value (EAV) and production costs (PC)) of the cultivation of SRWCs for bioenergy at the POPFULL plantation and the sensitivity of these values for changes in the key parameters

Parameters(1)		Farmer				Investor			
		NPV	EAV	PC	PC	NPV	EAV	PC	PC
		€ ha^{-1}	€ ha^{-1} y^{-1}	€ odt^{-1}	€ GJ^{-1}	€ ha^{-1}	€ ha^{-1} y^{-1}	€ odt^{-1}	€ GJ^{-1}
	Baseline values	**229**	**16**	**78.4**	**4.1**	**-485**	**-35**	**83.5**	**4.4**
Yield	Decrease -50%	-4962	-354	145.7	7.6	-5677	-405	155.1	8.1
(12 odt ha^{-1} y^{-1})	Increase +50%	5421	386	53.6	2.8	4706	335	57,1	3.0
Discount rate	Decrease -50%	1134	67	73.6	3.9	395	23	77.8	4.1
(4% y^{-1})	Increase +50%	-432	-37	83.8	4.4	-1134	-96	90.0	4.7
	Increase +300%	-1931	-323	122.0	6.4	-2628	-440	137.2	7.2
Land rent	Decrease -50%	2164	154	64.6	3.4	1450	103	69.7	3.6
(250 € ha^{-1} y^{-1})	Increase +50%	-1706	-122	92.1	4.8	-2420	-173	97.2	5.1
	Decrease -100%	4099	292	50.8	2.7	3385	241	55,9	2.9
	Increase +100%	-3640	-260	105.9	5.6	-4355	-310	111.0	5.8
Biomass price	Decrease -50%	-5389	-384	78.4	4.1	-6104	-435	83.5	4.4
(40 € Mg^{-1})	Increase +50%	5847	417	78.4	4.1	5133	366	83.5	4.4

(1) The baseline values of the studied parameters are presented between brackets.

Simulations from the POPFINUA model based on field data obtained from the POPFULL plantation have provided production cost values for woody chips from SRWCs in Flanders ranging from 4.1 to 4.4 € GJ^{-1} in the base case scenarios (Table 7.1). The figures are at the higher end, but still within the range, of the abovementioned values for SRWCs. Various assumptions are made when calculating the production costs and the profitability of SRWCs. Therefore, a sensitivity analysis was carried out to evaluate the impact of the most important variables on the results (Table 7.1). Table 7.1 shows that the biomass yield and the biomass sales price have the largest impact on the NPV and the EAV. A yield increase of 50% (from 12 to 18 odt ha^{-1}) would trigger an increase of the NPV and the EAV from 215 to 5407 € ha^{-1} and from 15 to 385 € ha^{-1} y^{-1}, while decreasing the production costs to 2.8 € GJ^{-1} in the farmer's scenario. The same percentage increase of the biomass price shows a comparable increase of the NPV and the EAV. Both the yield and the biomass price show considerable potential for increase. Dry matter yields between 20 and 25 odt $ha^{-1} y^{-1}$ have been reported under optimal conditions [7–9]. SRWCs yield is a function of survival, weed competition, site and microsite variation, and their interactions. Further improvements through breeding programs and optimization of both weed treatment and soil management could increase the yield. Fertilization programs are ongoing to detect the optimal level of fertilization and to decrease both the financial and environmental costs of fertilization. Consideration should be given to determining biologically and economically optimal fertilization schemes for SRWCs in the near future [10,11].

Rapidly rising energy prices and improved bioenergy conversion technologies are also affecting biomass sales prices [12]. While in 2004 average prices for coal, crude oil and natural gas amounted to ca. 1.7, 3.1 and 4.6 € GJ^{-1} respectively [13], these prices have raised to ca. 3.6, 14.3 and 6.4 € GJ^{-1}, respectively, in 2011 [14]. These rising prices do not only improve the competitiveness and attractiveness of biomass as a substitute for fossil fuels, but also raise the biomass sales prices, and thus increase the revenues of the biomass producers.

Despite the improved competiveness regarding fossil fuels, SRWCs will only by adopted at large scale by farmers if the profits of these energy crops compare favorably with other (agricultural) crops. A recent detailed study of Raes et al. [15], published by the Flemish Department of Agriculture and Fisheries, makes it possible to put the calculated profits of the POPFULL SRWC plantation into perspective. Table 7.2 provides the average gross profits for potatoes, winter wheat and sugar beet for Flemish farmers in 2010, ranging from 965 to 3396 € $ha^{-1} y^{-1}$. Unfortunately, these figures cannot be compared straightforwardly with the annual values for SRWCs (EAV in Table 7.1). The values for agricultural crops only take into account the variable costs whereas the values for SRWCs were calculated using a full cost approach taking into account both variable costs and assigned fixed costs. However, a closer look at the aggregated farm profits of 2010 shows that Flemish arable farms made a profit of 465 € ha^{-1} if subsidies and remuneration for own labor were excluded [15]. In 2010, the average subsidies for specialized arable farms amounted to 463 € ha^{-1}, while the remuneration for own labor was estimated at 838 € ha^{-1}, yielding a net operating profit of 90 € ha^{-1} [15]. Thus, the POPFULL SRWCs plantation only needs a subsidy of 69 € $ha^{-1} y^{-1}$ to yield comparable annual profits. Despite the importance of government support for the financial profitability of bioenergy, there are no (financial) incentives specifically aimed at supporting the cultivation of SRWCs for bioenergy in Flanders anymore. A limited incentive of 45 € ha^{-1} for Flemish farmers cultivating energy crops was rescinded in 2010 [16]. However, farmers are granted support under the Single Payment Scheme of the European Common Agricultural Policy (CAP) upon activation of payment entitlement per eligible hectare. Agricultural parcels planted with short rotation coppice which were maintained in good agricultural condition are eligible [17]. These activated payment entitlements give a right to the payment of an annual amount per hectare, averaging 491 € ha^{-1} in 2009 in Flanders [18].

Table 7.2 Gross profits of arable farming in Flanders – 2010. [15]

Agricultural crop	Gross profit – 2010 € ha^{-1}
Winter wheat	1473
Sugar beet	3396
Potato	965

2 Greenhouse gas and energy balance of SRWCs for bioenergy

To draw a complete picture of the performance of the cultivation of SRWCs for bioenergy, one can not only focus on its financial feasibility. Therefore, this dissertation shed more light on the GHG and the energy balance of these dedicated energy crops. A review and synthesis of the available information on these topics in the scientific literature indicated that SRWCs achieve GHG emission reductions and higher energy yields per unit non-renewable energy input compared to fossil fuels. The analysis resulted in values for the energy ratio (i.e. the ratio of the usable energy output to the fossil energy input) between 13 and 79 for the cradle-to-farm gate and between 3 and 16 for the cradle-to-plant assessments. The intensity of GHG emissions ranged from 0.6 to 10.6 g CO_2 eq $MJ^{-1}_{biomass}$ and from 39 to 132 g CO_2 eq kWh^{-1}_{e}, respectively. The GHG emission intensities found for electricity production from SRWCs are not only lower than all fossil fuels and but also lower than the life cycle emissions from electricity from solar panels (Table 7.3).

Table 7.3 Ranges for GHG emission for the production of electricity from various energy sources. [19–21]

Energy source	GHG intensity $g\ CO_2\ eq\ kWh^{-1}$
Coal	1080–1800
Oil	720–1080
Natural gas	360–720
EU grid mix (excl. nuclear)	832
EU grid mix (incl. nuclear)	564
Nuclear	18–108
Hydro	1.8–36
Wind	3.6–36
Geothermal	7.2–36
Photovoltaic	54–144
Biogas	54–234
SRWCs - Literature	39–132
SRWCs - POPFULL	256–272

The energy ratios and the GHG emission intensities differed considerably among the reviewed studies due to different system boundaries and calculation methods. The remaining variability of the energy ratio is explained by the amount and types of fertilizers, the harvesting method, and the assumption about the biomass yield. The wide range of GHG emissions can be attributed to agrichemical inputs (mainly fertilizers) and assumptions about nitrous oxide (N_2O) emissions associated with fertilizer input and decomposition of leaf and litter. Although a meaningful comparison among studies is hampered by the lack of transparency and the use of different indicators for energetic performance, this analysis has shown that limiting the agrichemical inputs has a significant beneficial impact on both the energy and GHG balance of SRWCs.

This review study is complemented with a case-study in which field measurements from the operational POPFULL plantation and a life cycle assessment (LCA) approach were combined to calculate the GHG emissions during the life cycle and related to direct land use change, the energy balance and the land requirement for the production of electricity from SRWCs. For this purpose, all farm labor, materials, and fossil fuel inputs to the bioelectricity production were traced back to the primary energy level. In addition, soil organic carbon was sampled and the fluxes of GHGs between the SRWC plantation and the atmosphere were monitored. This assessment considered two different conversion technologies, combustion and gasification, and showed that the production of electricity from SRWCs was energy efficient in both cases, yielding energy ratios between 3 and 3.3 over a two-year rotation. These energy ratios are at the lower end of the ranges found in literature (3 to 16) due to short time span considered (two years) and the low biomass yield (4 odt^{-1} ha^{-1} y^{-1}). Most of the energy inputs are required at the establishment of the plantation, namely for ploughing, pre- and post-emergent herbicide treatments, planting, etc., and are to be compensated by accumulating biomass yield over the entire lifetime of the plantation (up to 21 years). Consequently, the timeframe is an important factor for calculating this type of results.

The case-study also revealed that direct land use change (dLUC) is the most decisive factor in the overall GHG emission of the production of electricity from SRWCs, representing ca. 89% to total GHG emission (256–272 g CO_2 kWh_e^{-1}) over a two-year rotation. The calculated GHG emission intensities for the POPFULL plantations are below GHG emission values of fossil fuels and EU non-renewable grid mix power, but well above the maximum values found in literature for SRWCs (39 to 132 g CO_2 eq kWh_e^{-1}). This is mainly due to the inclusion of dLUC in the system boundaries, which was ignored in all reviewed articles. Excluding dLUC emissions from the system boundaries yields GHG emissions from bioelectricity between 29 and 31 g CO_2 eq kWh_e^{-1}, which are in line with the literature values.

Again, one should note that over longer periods of time there are substantial carbon sequestration effects of the formation of a root system of SRWCs. The net carbon benefits of a SRWC plantation are site specific, depending a.o. on the soil type, initial carbon content of the soil and climatic conditions [22]. In particular on marginal and degraded land and land previously used for agricultural crops as potatoes and beet one can see substantial improvement and additional carbon stock build-up [23–26]. Over a 20 year period, the carbon emissions of the carbon present in the soil would also be spread out over a longer period and compensated by accumulating biomass yield, largely improve the GHG balance. Studies [22,27] have indeed shown that rotation length is a key factor in the ability of plantations to accumulate carbon from the atmosphere and sequester it as soil carbon.

N_2O and methane (CH_4) emissions are also important variables in the assumed climate neutrality of SRWCs, given their high global warming potential over 100 years, respectively 300 and 24 times higher than CO_2 [28]. At the POPFULL plantation most of the N_2O emissions occurred shortly after the land use change, in the wake of the first heavy rainfall after a long dry period. The N_2O emissions in this single week represented ca. 42% of the total N_2O emitted in the two years of measurement [29]. The plantation was also a source of CH_4, but these emissions accumulated more gradually over the measurement period [30]. These positive cumulative emissions more than offset the CO_2 uptake, and turned the POPFULL SRWC plantation from a net CO_2 sink into a small source of GHGs, highlighting the important role of these emissions in the total GHG emissions associated with dLUC.

Although this dissertation focused on measurable environmental impacts, the discussion on indirect land use change (iLUC) cannot be ignored. Since the cultivation of SRWCs on agricultural land may trigger land conversion elsewhere in the world, releasing GHG emission through indirect land use change (iLUC), a more elaborate assessment should include both dLUC and iLUC. The iLUC occurs when forest, grassland or land dedicated to other uses is converted to new cropland to produce food, fibre or feed that were displaced by the expansion of bioenergy crop production [31,32]. While a sole focus on dLUC may produce positive results for many bioenergy chains, the inclusion of iLUC may lead to less or possibly no GHG emission reductions in reality [32]. Recent studies have shown that converting carbon-rich lands (e.g. forests, grasslands) to new cropland to replace the cropland diverted to bioenergy will lead to net carbon emissions for decades or centuries [32–34]. Policy makers should consider these potential harmful impacts of iLUC on the sustainability of bioenergy crops, certainly in the light of the projections that additional European demand for biofuels is anticipated to lead to between 4.1 and 6.9 Mha of iLUC by 2020 [35].

To date, analyses of iLUC have typically relied on economic models that simulate the impact of increased crop demands on international commodity markets and forecast spatially explicit growth in crop cultivation [31]. The area size and the localization of iLUC can only be roughly estimated, as they result from complex interactions between market fluctuations, global trade, weather variability and agricultural subsidy schemes [23]. Future research should not only focus on improving these iLUC models to increase our understanding of the full impact of iLUC of energy crops, but also on strategies to mitigate iLUC by more efficient farming and the deployment of marginal and degraded lands [31,33]. Since degraded and marginal lands are mostly unsuitable and economically unattractive for agricultural crops, there is no (in)direct competition with food/feed production or other land uses [36].

3 Stimulating policy for electricity from renewable energy sources

Section 1 has mentioned the need of government support in most regions, including Flanders, to make the production of SRWCs for bioenergy financially viable. The evolution of SRWC plantations in Sweden is the best example of the tremendous impact of support policies on the deployment of these energy crops. During the period of 1991–1996, high establishment grants (1200 € ha^{-1}) covering almost 100% of the starting costs of willow SRWC plantations were available for Swedish farmers [37]. At the same time taxes on sulphur and CO_2 for the use of fossil fuels were introduced, which were progressively increased in the following years [38,39]. The exemption of biofuels from these taxes resulted in the improved competitiveness of biomass [40]. Consequently, the area planted with willow SRWCs increased from almost zero to above 15000 ha between 1991 and 1996, making Sweden the leader of SRWC plantations in Europe [37,40]. However, since 1997 the expansion of willow SRWC plantations has ceased due to the reduction of the establishment subsidies to less than one third of the initial amount [40]. This reduction seriously affected the financial balance of SRWC cultivation, which is considered as a long-term investment as the cultivation time is estimated to be 20–25 years, and the crop is harvested every 2–5 years. In Flanders, the lack of adequate support measures focusing on the cultivation of dedicated energy crops is one of the main reasons for the absence of commercial SRWC plantation.

However, Flanders –similar to a large number of countries and regions around the world– has a support scheme designed to promote the production of RES-E. This dissertation evaluated the Flemish support scheme for RESE-E and its 2013 reforms, to reveal the missed opportunities. Since limiting this study to bioenergy only did not allow a comprehensive analysis, all renewable energy sources and technologies of relevance for Flanders were included. The most important shortcomings of the Flemish (tradable) green certificate (TGC) scheme are the high excess profits and the lack of qualification of renewable energy technologies. In 2013, the Flemish government introduced 'banding' to differentiate the support for various renewable energy categories. Banding implies the assignment of a different number of certificates per MWh of renewable electricity supplies depending on the renewable energy technology deployed [41]. Lack of adequate qualification of the renewable energy technologies and questionable calculation of the support levels, however, resulted in a limited and incomplete differentiation in Flanders. A fine-tuning of the support, as demonstrated by the German feed-in tariff (FIT) scheme, is still a long way off. In contrast with a FIT scheme, a TGC scheme overrides qualification by design requiring ad-hoc modifications to include technology differentiation. Haas et al. [42] argued that a well-designed FIT system with a dynamic technology-specific tariff structure that takes learning into account is preferred over a tradable certificate scheme. The United Kingdom also has a quota obligation system with tradable certificates and introduced banding to weigh the various certificates in 2009. However, in April 2010 – only one year after the introduction of technology bands – a FIT scheme for small-scale RES-E technologies (up to 5 MW) was introduced, further complicating the RES-E support(s) [43].

Quota based TGC systems show low effectiveness and higher costs, due to the missing qualification [42,44]. A simulation exercise comparing the Flemish TGC scheme with the FIT scheme using the German FIT levels for 18 reference units proved that Flanders still provides higher profits as compared to Germany for the majority (11) of the reference units. Differences between both systems were up to 45% in total revenues generated. The higher level of risk and uncertainty for investors, due to the unknown price of electricity and TGC values, have an impact on the required return on investments for investors. The 2013 reforms of the Flemish TGC scheme further increase the risks for RES-E investors, because the terms of the system can be altered by retroactive adjustment of support levels and by political intervention.

Despite these observations, it is still too early to determine the impact of the implementation of the 2013 TGC reforms on RES-E deployment levels in Flanders. However, given the considerable decrease of support for biogas units for the recuperation of landfill gas and for the digestion of sewage treatment sludge and municipal solid waste incineration plants, it is likely that investments in these technologies will be cut back. The retro-active limitation of TGC assignment to a period of ten years for projects commissioned before the reforms (i.e. before January 1, 2013) might also decrease the profitability and thus the competitiveness of RES-E plants older than ten years, in particular biomass plants given their considerable operational and fuel costs.

4 Conclusions and recommendations

In summary, this doctoral dissertation showed that a multidisciplinary approach including the financial, energetic and environmental perspectives is essential in the assessment of the performance of SRWCs for bioenergy. Based on literature and field data, it became clear that the cultivation of these dedicated energy crops is financially not profitable in a large number of regions across the globe, including Flanders, without government support. Although the increasing fossil fuel prices improved the competitiveness of SRWCs, their cultivation still requires additional financial aid to be profitable from a farmer's point of view. However, given the beneficial impact of SRWCs on the greenhouse gas emissions, and the high energy efficiency demonstrated, the development of adequate support measures to stimulate the wide deployment of SRWCs for bioenergy can be justified. Although no specific support measures aimed at the promotion the cultivation of SRWCs for bioenergy are available in Flanders, SRWCs are eligible for agricultural grants via the European CAP. Also the Flemish RES-E support scheme does not provide any specific support (or bonuses) for conversion plants using biomass from SRWCs as a feedstock. Future renewable energy policy reforms should be aimed at a better qualification of different renewable energy source-technology combinations to identify and target the most promising combinations from socio-economic point of view.

The establishment of operational scale plantations over multiple rotations, such as the POPFULL SRWC plantation, to assess the financial, environmental and biological performances of SRWCs (and other dedicated energy crops) is indispensable to gain insight in performance of these crops in other settings and on other land types (in particular on degraded and marginal land). This dissertation has shown that the lack of experimental data, and therefore inevitable dependence on models, has given rise to considerable variation in published results of both the financial and the environmental performance. Such large operational plantations could also allow for detailed studies on SRWC harvesting machines, particularly on the wet fields in Western European countries, to improve their efficiency and to decrease the harvest losses. Additionally, future research should focus on the long-term carbon sequestration potential of SRWCs, considering the impact of the different (previous) land uses, the soil type and the initial soil carbon level. In-depth research and more widespread, longer term datasets are also needed to increase our knowledge of the drivers of GHG emissions of SRWC plantations (fertilizers, farming practices, etc.) and the variables explaining the emission patterns.

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Nederlandse samenvatting

Het huidige, door fossiele brandstoffen gedomineerde, energiesysteem is niet duurzaam door de bijdrage van de verbranding van deze brandstoffen aan broeikasgasemissies, de eindigheid van de fossiele grondstoffen en de ongelijke verdeling van deze grondstoffen over de wereld. Via het gebruik van hernieuwbare energiebronnen kunnen de emissies van broeikasgassen worden gereduceerd en de opwarming van de aarde tegengegaan. Bio-energie, en energiegewassen in het bijzonder, worden geacht een centrale rol te spelen in de ontwikkeling van hernieuwbare en duurzame energiebronnen. Om deze rol echter te vertegenwoordigen, is een accurate kwantificering van de bijdrage van intensief beheerde bio-energie plantages, in het bijzonder korte-omloop hakhout (KOH) plantages, aan de vervanging van fossiele brandstoffen, en dus aan de vermindering van de emissies van o.a. atmosferische CO_2, noodzakelijk. Daarnaast is het essentieel om de financiële haalbaarheid van deze energiegewassen, rekening houdende met (eventuele) overheidssteun, in kaart te brengen. In dit licht was het hoofddoel van dit doctoraatsonderzoek de opstelling van een volledige financiële, energetische en broeikasgasbalans van een bio-energieplantage met snelgroeiende populieren en wilgen gebaseerd op zowel literatuur als observationele gegevens, met een uitbreiding naar de rol van de overheid in de bevordering van het hernieuwbare energiegebruik. Observationele gegevens met betrekking tot energiegebruik en -productie, koolstofinputs en -outputs, alsook financiële data werden bekomen van een grootschalige operationele bio-energieplantage in Lochristi, België (POPFULL).

Het eerste deel van dit proefschrift onderzocht de financiële haalbaarheid van KOH voor bio-energie in verschillende landen en regio's over de wereld met een focus op het methodologisch kader. De analyse toonde aan dat studies zeer verdeeld zijn wat betreft de haalbaarheid en de eventuele rendabiliteit van KOH-plantages, maar dat in de meeste regio's de teelt van KOH niet rendabel is zonder overheidssteun. Hoewel een deel van de gevonden variatie kan toegeschreven worden aan verschillen in teeltechnieken en biomassa-opbrengst, spelen (regionale) verschillen in de kost van productiefactoren en de gebruikte berekeningsmethodes en een belangrijke rol. Gebaseerd op de methodologische bevindingen uit deze analyse werd een gedetailleerd cash-flow model ontwikkeld om de financiële haalbaarheid van de operationele POPFULL plantage in Lochristi te onderzoeken. Deze financiële analyse heeft aangetoond dat ook in Vlaanderen KOH (nog) niet rendabel kan worden geteeld, onder meer te wijten aan de lage biomassaprijs en de relatief hoge pachtkosten voor landbouwgrond. Hoewel de stijgende prijzen van fossiele brandstoffen de concurrentiepositie van KOH verbeteren, is er nog steeds financiële steun vereist om deze gewassen rendabel te kunnen telen.

In het tweede deel van het onderzoek werd nagegaan in hoever het gebruik van KOH voor de productie van elektriciteit voordelen biedt op het vlak van broeikasgasemissies en of dit energetisch efficiënt is. Uit een uitgebreide literatuurstudie is gebleken dat, ondanks de grote verschillen in gepubliceerde data, de productie van KOH voor bio-energie emissies uitspaart en meer energie oplevert dan erin geïnvesteerd is. Een gedetailleerde analyse van de belangrijkste broeikasgasemissies (CO_2, N_2O en CH_4) en de energiebalans van de POPFULL plantage heeft aangetoond dat zelfs op zeer korte termijn (2 jaar) de teelt van KOH voor elektriciteit emissies vermindert door het uitsparen van fossiele brandstoffen en energetisch rendabel is, ondanks de hoge initiële kosten – in termen van energiegebruik en broeikasgasemissies – die noodzakelijk zijn voor de opstart van de plantage.

Het derde en laatste deel van dit doctoraatsonderzoek is dieper ingegaan op de recente (2013) hervormingen van het Vlaamse hernieuwbare energiebeleid. Hervormingen waren noodzakelijk omdat sommige toepassingen te veel en te lang gesubsidieerd werden, onder meer door een gebrek aan differentiatie in de toegekende steun. Het onderzoek toont aan dat het ondersteuningsmechanisme na de hervormingen nog steeds tekortschiet in de ondersteuning van veelbelovende hernieuwbare energietechnologieën door een blijvend gebrek aan accurate kwalitatieve inschaling van de verschillende technologieën. Bovendien wordt de investeringszekerheid nog verder ingeperkt door een gebrek aan lange-termijn perspectieven en door de nieuwe mogelijkheid om de hoogte van het steunniveau retroactief aan te passen.

List of publications

Peer-reviewed articles

Njakou Djomo S., El Kasmioui O. and Ceulemans R. (2011) Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *Global Change Biology – Bioenergy*, 3:181–197. doi:10.1111/j.1757–1707.2010.01073.x

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