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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.

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.

1. 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 above-mentioned 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 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].

2. 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 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 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.

3. 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.

3.1. 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.

3.1.1. 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 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 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. 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 Fig. 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 100-400 € ha^{-1} y^{-1} [27] and between 75-250 € ha^{-1} y^{-1} [23], and establishment costs of 2 632 € ha^{-1} [28] and 2 173 € 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 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.

3.1.2. 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.

3.2. 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.

3.2.1. 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):

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

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.

3.2.2. 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):

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

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 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.

3.2.3. 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 LC_t = levelized cost at time *t*, C_t= expenses at time *t*, Y_t=biomass yield 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.

3.2.4. 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.

3.2.5. 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):

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

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.

4. 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 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

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

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].

5. 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 consequent 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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Table 1: Overview of 23 reviewed studies including the main objectives and conclusions of each study, as well as the calculated values and the calculation technique employed

Country	Objectives of the study	Stages	Point of view	Calculation method	Calculated values	Data	Main conclusions	Reference
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	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]
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	DCF (5% y^{-1}) – LC, NPV, EAV	PC, CNM, ANM	L/M	The interest rate, subsidies, the yield and 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]
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	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]
Canada	Economic viability of bioenergy from poplar SRWCs on agricultural land using a bio-economic afforestation feasibility model	Cradle-to-plant gate	F	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]
Chile	Assessment of the potential production costs of four cultivation regimes (*Populus, Salix, Eucalyptus and Pinus*) for energy	Cradle-to-farm gate	F	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]
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	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]
Denmark & Sweden	Energetic, economic and ecologic balances of an integrated agricultural systems compared to simple fallow on set-aside land	Cradle-to-plant gate	F	DCF (7% y^{-1}) – NPV	CGM	L	Combined food and energy systems can be beneficial from both farmers' and social point of view	[38]
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	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]
Ireland	Life cycle cost assessments to compare the production costs of Miscanthus and willow with conventional farming	Cradle-to-farm gate	F	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	[29]

	systems in Ireland						investment risk considerably	
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	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]
Ireland	Energetic, technical and economic potential of willow SRWCs, forest residues and sawmill residues for power generation	Cradle-to-plant gate†	F	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]
Italy	Energetic, economic and environmental analysis of poplar SRWCs in the Po Valley area	Cradle-to-farm gate	F	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]
Italy	Economic and energetic assessment of poplar SRWCs in the western Po Valley	Cradle-to-plant gate	F	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]
Poland	Economics of growing willow on large farms and comparison of viability of growing willow to wheat and barley	Cradle-to-plant gate	F	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]
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	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]
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	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]
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	DCF (4.75% y^{-1}) – NPV, EAV	PC, APC, CPC	L/M	Polar SRWC for electricity generation is an economically feasible option in Spain and the balance can be improved by selling CO_2 emission credits	[26]
Sweden	Describing the main properties of willow wood, the production stages of willow SRWC and the economic feasibility	Cradle-to-plant gate	F	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]
UK	Summary of the results and observations of larger scale field trials with SRWCs	Cradle-to-plant gate	F	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	[46]

							at commercial scale	
UK	Full economic assessment of willow SRWCs, including a brief sensitivity analysis in Wales	Cradle-to-plant gate	F	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]
USA	Summary and comparison of production cost, supply curve, transportation cost studies considering switchgrass, poplar and willow	Cradle-to-farm gate Cradle-to-plant gate	F	DCF (6.5% y^{-1}) – NPV	PC, CPC	L/M	Huge difference 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]
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	DCF (5% y^{-1}) – See section 4.2.4.	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]
USA, NY	Economic analysis of willow SRWC 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	DCF (6% y^{-1}-10% y^{-1}-15% y^{-1}§) – 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]

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: Original data = O; Literature = L; Modeled = M

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 SRWC 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

Table 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)	Species	Rotation length (years)	Calculation period (years)	Included costs	Reference
Farm gate	Belgium	12	3.97	Willow	3	26	Fixed costs, variable costs, land rent	[40]
Farm gate	Chile	15-25[2]	3.5 - 3.9	Willow	5	15	Variable costs, land rent	[37]
Farm gate	Chile	10-12[3]	4.1- 4.4	Poplar	8	15	Variable costs, land rent	[37]
Farm gate	Ireland	8.8	1.7-2.6	Willow	3	23	Variable costs	[29]
Farm gate	Italy	18	3.27	Poplar	5	10	Variable costs, land rent	[20]
Farm gate	Spain	13.5	0.8-0.85	Poplar	5	16	Fixed costs, variable costs, land rent	[26]
Farm gate	USA	11.23	3.27	Willow	3	22	Fixed costs, variable costs, land rent	[22]
Farm gate	USA, NY	14.8[4]	1.5	Willow	3	22	Variable costs, land rent	[24]
Plant gate	Czech Republic	10	3.3	Poplar	3	21	Fixed costs, variable costs, land rent	[30]

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

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

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

Plant gate	European Union	9	4-5	Willow	3	22	Fixed costs, variable costs, land rent	[32]
Plant gate	Poland	9	1.4[5]	Willow	3	22	Variable costs	[32]
Plant gate	Ireland	12	2.8	Willow	3	22	Variable costs	[31]
Plant gate	Ireland	9	3.4	Willow	4	25	Variable costs	[25]
Plant gate	Italy	10	4.1-4.9[6]	Poplar	2	8	Variable costs, land rent	[27]
Plant gate	USA	16	2.3	Poplar	6	12	Variable costs, land rent	[18]

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.

[5] Converted from MWh into GJ, costs are lower thanks to lower costs of labor, diesel and fertilizers in Poland
[6] The higher the cultivation surface, the lower the production costs, in this case surfaces of 50 ha and 100 ha were considered

Fig. 1: Farm gate (left figure) and plant gate (right figure) biomass production costs for different countries as compared to the delivered cost of coal based on data from Table 2