ECONOMIC VIABILITY OF PHYTOREMEDIATION OF AN AGRICULTURAL AREA USING MAIZE: PART II

ECONOMICS OF ANAEROBIC DIGESTION OF HEAVY METAL CONTAMINATED MAIZE IN BELGIUM

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Abstract

This paper deals with remediation of the Campine soil, an agricultural area diffusely contaminated with heavy metals where most farmers rear dairy cattle and grow fodder maize. In part I of this study (Witters *et al.*, xxx), the effect of switching from fodder to energy maize on the income of the farmer was calculated. Selling this energy maize as feedstock for anaerobic digestion to produce renewable energy could lead to a significant increase in the farmer's income. Part II explores the economic opportunities for the farmer of digesting the harvested contaminated biomass himself, by performing a Net Present Value (NPV) analysis concerning the digestion activity and by calculating the probability of a positive NPV of income resulting from the digestion installation. We investigate the trade off between the maximum price for energy maize that can be paid by the digestion activity and the minimum price that the farming activity needs to compensate for covering its production costs. Integrating the previous article in the actual analysis results in an increase of the total extra income for the farmer (i.e. from both growing energy maize and performing digestion).

Keywords: Heavy metals, Campine, Agriculture, Phytoremediation, Phytoextraction, Anaerobic digestion, Cost-benefit analysis, Sensitivity Analysis

1. Introduction

1.1. Combining phytoextraction with bioenergy production

The practical implementation of phytoremediation has been constrained by the expectation that site remediation should be achieved in a time comparable to other clean-up technologies. This time constraint may become less important if phytoextraction can be combined with a revenue earning operation (Robinson *et al.*, 2003; Ghosh and Singh, 2005; Meers *et al.*, 2005; 2006). Decontamination of soil is a long term goal that can be achieved by striving for short term goals like producing renewable/green energy to keep the income of the farmers at a level comparable to the situation before the start of remediation (Vassilev *et al*., 2004). Against this background we opt to investigate the economic viability of energy maize. The farmers involved in this case study are mainly dairy cattle farmers who wish to continue their activities. In the Campine, a farmer possesses 40 ha of land; he uses about 50% to grow fodder maize. The other 20 ha are used as grassland for the cattle (Federal Public Service Economy, 2006; own calculations).

The effect of the switch from fodder to energy maize on the dairy cattle activities has been described in part I: 'Impact on the farmer's income' (Witters *et al*., xxx). In that first scenario, the cost of phytoremediation for the farmer had to be compensated by revenues coming from selling energy maize. The energy maize can then be used as a feedstock in a dry digestion installation, i.e. an installation fed with biomass with a high (>15%) dry matter percentage. The latter is further elaborated in the second scenario, described in this part. The farmer has two main activities: he grows energy maize while continuing his dairy cattle rearing (fed with unpolluted bought fodder maize), but he is also managing a digester (in cooperation with other farmers). Extra revenue might then be generated for the farmer by the digestion activity. Therefore, we will analyse whether it is economically achievable for local farmers involved in a phytoremediation project to run a digestion installation fed with polluted biomass, given base case values for predefined variables.

1.2. Anaerobic digestion of contaminated energy maize

Anaerobic digestion is the conversion process where organic matter of biomass is converted into methane in four phases by bacteria in the absence of oxygen. The end products of the digestion process are biogas and digestate. Due to its high energy content, biogas can be used in engines and machines that work on natural gas, be used as a transport fuel or even be injected in the natural gas distribution network (Verstraete, 1981; Ramage and Scurlock, 1996). In this study we will opt for the first choice, burning the gas in a gas engine with heat recovery, in a Combined Heat and Power engine (CHP). The other product that comes out of the digester is the digestate, a mixture of water and stabilized organic matter. All the metals present in the biomass end up in this digestate. In general, digestate is a good alternative to chemical fertilizer and in addition is more stable than undigested manure, with a better humus performance (Timmerman, van Dooren and Biewenga, 2005).

1.2.1. The effect of heavy metals on the digestion process

Information, data and studies relating to the potential influence of metal concentrations in the biomass on the digestion process are scarce. Heavy metals have a proven effect on the enzymes responsible for the break-down of biomass particles. Whether they stimulate or inhibit biogas production is depending on total metal concentration, the chemical form of the metals and process related aspects (Chen, Cheng and Creamer, 2008). Pahl *et al*. (2008) found in their experiment with co-digestion of mechanically biologically treated municipal waste containing heavy metals and sewage sludge evidence of the accumulation of heavy metals in the digester. According to Marchaim (1992), certain heavy metals (not specified) can be toxic to anaerobic organisms, even at low concentrations. The heavy metal ions kill organisms by inactivating groups of their enzymes and thus inhibit digestion. The relative sensitivity of acidogenesis (the phase where acids are formed) and methanogenesis (final phase where methane is formed) to heavy metals is Cu > Zn > Cr > Cd > Ni > Pb and Cd > Cu > Cr > Zn > Pb > Ni, respectively (Chen *et al*., 2008).

Wong and Cheung (1995) conducted experiments on digestion of heavy metal contaminated sewage sludge and concluded that presence of certain heavy metals always tends to reduce the biogas yield. The order of toxicity observed was Cr > Ni > Cu > Zn. Reversely, studies on water hyacinth

(*Eichhornia crassipes*), channel grass (*Vallisneria spiralis*) and water chestnut (*Trapa bispinnosa)* used as phytoremediating plants in industrial effluents, demonstrated that the slurry of these plants produces significantly more biogas than the slurry of control plants grown in unpolluted water (Verma, Singh and Rai, 2006; Singhal and Rai, 2003).

(table 1)

These experiments indicate the effect of heavy metals on the digestion process, but they do not offer us the opportunity to come to a conclusion concerning biogas production from polluted energy maize. Applied experiments about the effects of metals in phytoremediation biomass grown on Cd and Zn contaminated soil in the Campine experimental field on the anaerobic digestion process are currently ongoing (Van Slycken *et al*., 2008), the results of which will be forthcoming and published in the coming years.

1.2.2. The concentration of heavy metals in the digestate

As the organic fraction of the biomass is broken down during digestion (and metals are not), the concentration of heavy metals expressed on dry weight basis will increase (Kool *et al*., 2005). The concentration of metals in the digestate will be dependent on the ratio between organic matter and water content of the biomass input. Mass reduction on dry weight basis by conversion of biomass into biogas is approximately 50%. In the current case study, the residual digestate after digestion is further processed by separation into a liquid fraction (2% dry weight) and a solid sludge fraction (25% dry weight). The solid fraction is subsequently dried (DS 85%) using the heat recuperated from the CHP unit which is powered by the biogas generated by the anaerobic process. The fate of heavy metals during post-processing digestate and their manipulation is also the focus of ongoing research, yet falls outside the scope of the current economic assessment. Suffice it to say that the remediation process does not end at the phytoextraction and harvest of the phytoremediation crop, nor at the processing of this biomass during and after digestion, yet should include a full life cycle analysis of the targeted heavy metals from contaminated soil to their recuperation/re-use or safe disposal.

2. Data and methods

The basic income of the farmer will remain and will be supplemented or reduced with the positive or negative income from phytoremediation and energy activities (anaerobic digestion). The economic viability is evaluated by calculating the extra positive or negative income stemming from the digestion activity. The Net Present Value (NPV) of the stream of yearly net incomes (the yearly ‘cash flow’, CF) is calculated over the lifetime of the digestion installation. A project is accepted when the present value of the net income stream over its lifetime (NPV) is positive. To calculate the NPV, information is needed on the investment costs, yearly expenses and yearly revenues, based on several variables. The time scale (t) is 20 years. A discount factor (i) of 6% is assumed (Murphy and McKeogh, 2006; Maeng, Lund and Hvelplund, 1999). Eq. 1 gives the formula for the NPV. CF_0 is the initial investment cost of the project. CF_t is the cash flow in year t (t: 1 … n).

$$NPV = CF_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} \qquad \text{(Eq. 1)}$$

From this NPV the yearly extra income can be calculated (see appendix A). To take into account uncertainty about the numerical value of determining variables we use the technique of Monte Carlo simulation (using the software package Crystal Ball, Decisioneering Inc.). A run in this simulation calculates the NPV according to values randomly taken from the presupposed value ranges for predefined variables. The value ranges are defined as the most likely value ± 10%. The most likely value in the base case is determined as explained in §2.2 below. Performing numerous runs (in our study 20,000), this technique calculates numerous NPV’s of the net results, resulting in a distribution of the NPV’s together with the probability to obtain a positive NPV (Prob(NPV>0)). An analysis of this NPV indicates the most important variables determining profitability. Next, the most likely values of the most determining variables are changed in a negative way and their ranges accordingly (*ceteris paribus*) and the simulation for the NPV is run again. The results indicate the sensitivity of the NPV of the extra income from the digestion activity with respect to significant changes in the numerical values of the determining variables. Moreover, these variables are used to calculate the maximum price for energy maize as a feedstock that can be paid by the digestion activity not to become unprofitable. Finally, findings from both parts (I and II) are integrated, taking account of the ‘conflict of interest’, given the fact that the farmer acts as a seller (growing energy maize) and as a buyer (digesting energy maize).

2.1. Basic Model

To reduce risks associated with cultivating fodder crops on diffusely metal enriched agricultural land (Witters *et al*., xxx), the farmer will switch from fodder to energy maize while continuing his dairy cattle rearing activities at the same level and while continuing marketing dairy products as before. To continue business as usual for his dairy activities, he requires the same amount of fodder maize as before. In this study a fresh yield of 50 and 60 tons per hectare respectively for fodder and energy maize is assumed. Fodder maize will have to be bought outside the contaminated area. The cost of growing maize is independent of whether it is fodder or energy maize (per hectare). The basic income (from growing maize and selling milk products) will therefore be the same as before and is altered by buying fodder maize and selling energy maize. The economic viability of reclamation of the soil depends on the yield of fodder and energy maize, their relative prices and transport costs. This is explained in part I (Witters *et al*., xxx). Extra revenue might be generated by the digestion activity, as explained in this part.

2.2. Variable description

2.2.1. Number of farmers: dimension of digester and engine

The optimal number of participating farmers can be derived from the investment cost and thus dimension of the engine. The investment cost in the CHP is a logarithmic function of the size of the engine, where economies of scale apply starting from an engine with an electric capacity of 900 kWe. The investment cost of the digester has no effect as it is a linear function of the volume of feedstock and gas produced. Given the base case values for the variables and using Eq. 7 in appendix B, an engine with a capacity of 900 kWe results in an optimal number of participating farmers of 13.6. For ease of calculation, we assume this number to be 15 as the most likely value in the base case.

2.2.2. Price and relative yield of energy maize

From the point of view of the digesting activity, energy maize is the feedstock. Costs involve the price of energy maize, the transport cost ton^{-1} km^{-1}(T) and the ensiling cost. Transport costs are on behalf of the buyer of the biomass and as such are a revenue for the vendor of the biomass. Calculations for total transport costs can be found in Witters *et al.* (xxx). The cost of ensiling lies between € 55 and €93 ha^{-1} according to the Animal Sciences Group of Wageningen University (2006) and De Boer *et al.* (2003). Consistent with these estimates, the study performed by Goossens (2007) for OWS (Organic Waste Systems) assumes that the ensiling cost amounts to € 2 ton^{-1} FM. At the moment, farmers receive a price between € 1,800 and 2,000 ha^{-1} for fodder maize, depending on the yield per ha. In the base case we assume a price for energy maize of € 1,800 ha^{-1}. This is consistent with the yield of 60 ton fresh matter per ha and a price of € 30 ton^{-1} FM, as in the previous article (Witters *et al.*, xxx). The distribution of the yield of energy maize is determined relative to the yield of fodder maize, i.e. min. 1 (=50/50), most likely 1.1 (=55/50) and max. 1.2 (=60/50 ton ha^{-1}). The price and the relative (i.e. compared to fodder maize) yield of energy maize can be changed in the NPV-model.

2.2.3. Digestate

The digestate contains heavy metals - resulting from the uptake performed by maize - so a solution has to be sought with respect to the proper disposal or processing. The separation cost of the digestate is included in the initial investment cost of the digester at € 10 per ton input. Operating costs for separation lie around € 2 per ton digestate. The drying cost of the digestate consists for a large part of energy costs, these costs are assumed to be zero because it suffices to use all net produced heat. This means however that no heat can be sold. An extra drying cost of € 10 per ton solid fraction is used in the calculations. Transport costs of the dried solid fraction lie at € 3 per ton. The disposal cost of the dried solid fraction is estimated at € 5 ton^{-1} (the cost of disposal of the contaminated digestate can however become negative, indicating an income from selling the digestate) (Velghe, 2007).

2.2.4. Yearly revenues

2.2.4.1. Green Current Certificates (GC)

In Flanders, every electricity supplier is obliged to deliver a specific volume of electricity generated from renewable energy sources. The producers of so called 'green' electricity receive a certificate for every MWh (net) produced. Concerning green electricity produced by digestion, this refers to the electricity available net of the use in the digestion process, as indicated by a decision of the Flemish Government in 2004 (Flemish Government, 2004) and clarified by the Flemish Regulation Entity for the Electricity and Gas Market (VREG, 2007). The producers receive a minimum guaranteed price of € 80 per certificate guaranteed during 20 years. The current market price is situated at approximately € 112.5 per MWh, with only slight deviation from this number over recent years.

2.2.4.2. Combined Heat and Power Certificates (CHPC)

Another official incentive policy involves support for exploiting a gas engine in a combined heat and power system (CHP system). This system promotes that, besides the electricity produced, heat will be recovered for which the government issues Combined Heat and Power Certificates during 10 years. The minimum guaranteed price per certificate is € 27. Again the market price is higher than the guarantee and is currently situated at approximately € 40.5 per MWh, with only slight deviation from this number over recent years. To read more on this system, see appendix C.

2.2.4.3. Opportunity value of heat

In this study it is assumed that all net heat produced (i.e. after 4.1% is used by the digester as it concerns dry digestion and large investments in insulation are made by this specific installation) will be used. In the base case 100% of the net heat will be used to dry the digestate. However, if less heat is necessary to dry the digestate, the surplus heat can be sold and thus has an opportunity value. More specifically, the use of natural gas in a boiler can be omitted. This means a reduction in cost of € 27.5 MWh^{-1}, depending on the price of gas.

2.2.4.4. Opportunity value of electricity

Net electricity can be used locally or it can be put on the grid. The first option is called opportunity value of electricity. The opportunity value of electricity is obtained by multiplying the price normally paid for electricity by the farmer (most likely value of € 100 MWh^{-1} in the base case), with the sum of the amount normally used and the volume that can be sold at local consumers of electricity.

2.2.4.5. Price electricity sold to the grid

These are the revenues from selling net electricity produced (i.e. after process use) to the grid. In this study it is assumed that all net electricity produced is put on the grid, meaning that the opportunity value of this amount of electricity (§2.2.4.4) is zero. In the base case the selling price of electricity to the grid is € 80 MWh^{-1}, i.e. 80% of day-ahead electricity trading prices.

3. Results and discussion

3.1. Extra income using deterministic approach

In the base case, the yearly cash flows (CF) from year 1 onwards, necessary to calculate the NPV are as indicated in Table 2. Percentages are calculated relative to the total incoming and outgoing cash flows. The initial investment costs in year 0 are not shown explicitly. To calculate the NPV of the digestion installation, we use the most likely values of the determining variables as listed in Table 3. This base case results in a mean NPV of € 266,271. Per year and per hectare occupied by energy maize, this means an average extra income stemming from the digesting activity of € 77.4 ha^{-1}, i.e. the income that the digestion project can pay to the farmer for it still to be accepted as an economically viable project. This is an extra income, additional to the revenue from growing and selling energy maize (€ 166.5 ha^{-1} in the deterministic approach in part I).

(table 2)

To take into account the uncertainty involved however, we make an appeal to Monte Carlo simulations.

3.2. Extra income taking into account uncertainty

The Monte Carlo technique calculates different Net Present Values based on different values of the determining variables. The value for a specific variable is obtained as a randomly drawn value from a triangular distribution as explained in part I (Witters *et al.*, xxx). There is insufficient data to fit any other distribution but the minimum, maximum and most likely values are known or presupposed based on expert information. The variable specific minima, maxima and most likely values used in this study are found in Table 3. From this calculation of the NPV we can deduce the average extra income per hectare per year (see appendix A).

(table 3)

Given the assumptions in Table 3 (called the 'base case'), the average extra income per hectare is € 76.6 -to be compared with € 77.4, the result calculated in the deterministic case. The probability that the average extra income per hectare is not negative is 75.7%. Sensitivity analysis shows which variables contribute the most to the uncertainty of the forecasted average extra income. Table 4 shows that the variability in the price of green current certificates accounts for approximately 39% of the variance in forecast values and can be considered the most important determining variable in the model. As can be seen in the table, 87% of the variance in R is explained by the price of green current certificates, the price of energy maize and the price of electricity sold to the grid.

(table 4)

In the next section the effect on the average extra income per ha (*R)* and on the probability of getting a positive extra income from the digester of changing the most likely values of these three variables is calculated (*ceteris paribus*).

3.3. Analysis

3.3.1. Less favourable values for the determining variables

In the pessimistic scenario, the most likely values (and accordingly the minimum and maximum values) of the different income determining variables are changed in a negative way (*ceteris paribus*) compared to the base case. In doing this, we maintain the same distribution as in the base case (most likely value ± 10%). In table 5, column (5) we see the average extra revenue which can be earned by the digestion activity per year per hectare. In column (7) we see the result for the probability of obtaining a positive NPV and thus a positive *R*.

(table 5)

Row 1 confirms the importance of the Green Current Certificates for the economic viability of a digestion installation. If more certificates are traded on the market, prices might fall down with 10% and render the installation economically unfeasible. Moreover, these numbers confirm that the minimum price for Green Current Certificates *(ceteris paribus)* will certainly (in this project) not be able to render the installation viable. The price of energy maize is equally important. The large impact of a 10% raise in energy maize price on *R* and on Prob(NPV>0) is shown in row 2. In row 3, the price of electricity is lowered to a level where it was just some time ago. The price of electricity on the day-ahead market is far from constant. The effect of a 10% lower price reduces *R* with approximately €126. Changing the values of the three variables *(ceteris paribus)* with 10% reduces Prob(NPV>0) with 45-55%pt. The most likely value in the pessimistic scenario of the price of Combined Heat and Power Certificates (row 4) is set at € 30 MWh^{-1}, with a minimum of € 27 MWh^{-1}. This minimum guarantee leads to a probability of a positive NPV of 35.6%. Compared to the Green Current Certificates, a guaranteed minimum price for CHP certificates does provide a larger probability of a positive extra income. If the most likely number of farmers is reduced from 15 (base case) to 10 (row 5), the probability of a positive NPV of the digestion activity is reduced from 75.7 % (base case result) to 40.7 %. This can be explained by the fact that investment costs in digester and CHP engine are too high to be compensated by the yearly net cash flow generated by a smaller number of farmers. This is due to economies of scale occurring in dimensioning the CHP engine.

3.3.2. Contaminated digestate

The contaminated digestate will first be separated and then dried. By doing this it can be exported to a country like France that lacks fertilizers. The economic construction for drying the digestate is complicated. In the base case, it is assumed that all heat is used to dry the digestate. By consequence no net heat produced is sold and CHP certificates are granted for all net heat. In practice however, a digester does not receive certificates for the heat used to dry that part of the digestate coming from energy crops (Until now, there is no Belgian/Flemish legislation on contaminated energy crops. If they are considered as waste, then certificates are granted to dry the digestate coming from the crops). Therefore, in the base case all net heat is actually sold (to be used by a nearby swimming pool), the same amount of heat is bought at the same cost to dry the digestate (resulting in no net value for heat). As a result, certificates are granted for all net heat, as it is used by the swimming pool.

In this part of the analysis, let's see what happens if no certificates are granted for the heat used for drying the digestate. This heat thus has no economic value and no certificates are granted for it. The rest of the net heat is sold at a price of € 27.5 MWh^{-1} and certificates are granted for this part.

(table 6)

In Table 6, it is shown that when only 25% of net heat is needed to dry the digestate and 72% can be sold, there is a 100% chance to have a positive extra income from the digester. If however, 75% of net heat produced is needed to dry the digestate, extra revenues for the farmer are negative. If this is the case, a construction as in the base case might prove helpful, i.e. find local demand for all net heat, sell it and buy the amount of heat at the same price needed to dry the digestate. This way, farmers will receive certificates of € 40.5/MWh for all net heat. In the dry digestion process, 38% of the heat can be used to dry the digestate and still render the installation with relative certainty profitable (see row 2).

In the base case, it is assumed that disposal cost of the contaminated digestate is € 5 ton^{-1} digestate. Drying costs are € 10 ton^{-1} solid fraction. This drying cost has to go down to € 6, *ceteris paribus* in order to have a (Prob(NPV)>0)≈90% and resulting in an extra income of € 130.4 per hectare per year. Disposal costs can be €2.2 ton^{-1} digestate for the installation to have an almost certain positive effect on the income of the farmer (Prob(NPV)>0)≈90%, resulting in an extra income of €

136.2 per hectare per year. From the moment that the digestate can be disposed of at no cost or even be sold, there is a 98% chance on a positive extra income with a mean extra income of € 213.3 per ha per year.

3.3.3. Maximum price for energy maize as a feedstock as to Prob(NPV>0) ≈ 90%

What is the maximum price for energy maize that can be paid by the digester such that the probability of a positive NPV lies above the 90% range? To constrain conditions, the value of the NPV is calculated using the least favourable values for the variables.

(table 7)

In the second column of table 7, we find the most likely pessimistic values for the different chosen variables. In column (3), the maximum price that the digester can pay for energy maize per ton FM to have an almost certain positive NPV, is given. This Prob(NPV>0) appears in column (4). In column (5), the average revenue originating from the digestion process expressed per hectare of energy maize is calculated.

There is a conflict of interest in the determination of the price of energy maize. On the one hand, farmers want to receive a price for their energy maize that is as high as possible (part I). On the other hand, the price of energy maize is an important cost element of the digestion activity which is in the hands of the same farmers. The exact price from which the energy maize producer will sell to a digester–depending on *mE*, *mF*, *P*(fodder maize) and *T* - is calculated in part I (Witters *et al.*, xxx) and is recapitulated in Figure 1.

(figure 1)

The calculated prices that the digester can pay are compared with the price that the farmer wants to receive as a producer of energy maize. The figure should be read as follows. Given a base case relative yield mE/mF (i.e. 1; 1.1; 1.2) when the farmer has to buy fodder maize at a price of € 30 ton^{-1} he wants to receive a price of at least € 31.2 ton^{-1}. Given the base case relative yield, the relation between fodder maize price and energy maize price can be expressed as follows:

$$P(EM)= 0.96 \cdot P(FM) + 2.48 \qquad \text{(Eq. 2)}$$

Putting the prices for energy maize found in Table 7 in Eq. 2 gives maximum prices of fodder maize in € ha^{-1} between 24.0 and 27.3. Within this range, energy maize will be sold by the farmer to the digester at prices determined in Table 7. Consequently, the farmer selling his energy maize to the digester has a 90% chance to increase his income and at the same time the digester exploited by the farmer has a 90% chance to be profitable. Remind however that production costs of maize lie at € 1,200 ha^{-1}, resulting in a cost of € 24 ton^{-1} fodder maize below which the fodder maize will not be sold. In the next part, it is shown however that the condition of a Prob(NPV>0)≈90% simultaneously in both scenario's is too stringent in the integrated scenario. In the integrated scenario where the farmer produces energy maize, sells it to its own digester and produces electricity, heat and digestate, the probability of a positive extra income coming from both activities is cumulated.

3.4. Integration: Total income from cultivating and digesting energy maize

Collecting all influences from the analysis in part I (concentrating on the farmer's extra income from growing and selling energy maize and buying fodder maize) and part II (concentrating on the farmer's extra income from digesting the energy maize), the technique of Monte Carlo simulation allows the model to calculate the simultaneous influence on the income of the farmer of all considered determining variables. Table 8 (rows 1-4) gives an overview of the contribution of the determining variables to the variance of the forecasted extra income of the farmer (columns 2-4). The columns refer to the extra income resulting from selling the energy maize (column 2), the income from the digestion activity (column 3) and the total extra income for the farmer combining the two activities (column 4).

(table 8)

Given the base case values in part I, there is an 83% chance for an improvement of the farmer's income, resulting from growing and selling energy maize (row 7, col.2). The average extra revenue for the farmer then lies around € 114 $ha^{-1}y^{-1}$ (row 6, col.2). Given the base case values for the variables in part II, there is a 75.7% chance of obtaining a positive income from the digestion activity for the farmer (row 6, col.3), which means an average extra income per hectare of around € 76.6 ha^{-1} (row 6, col.3). Integrating both parts, Monte Carlo simulation results in a total average extra revenue for the farmer (i.e. from both growing energy maize and also performing digestion) of € 191.4 ha^{-1} y^{-1} (row 6, col.4). Moreover, the probability that this total extra income is positive, is almost 90% (row 7, col.4) when the farmer grows energy maize instead of fodder maize and simultaneously exploits the digester (in cooperation with other farmers). These results are based on the base case values of energy and fodder maize prices of € 30 ton^{-1}. Such an extra income would increase the actual labour income per ha per year originating from dairy cattle rearing (approximately € 1,123 ha^{-1} y^{-1} in 2005) by more than 15%.

Taking a closer look at the determining variables reveals that the variability of the yield of energy maize per hectare contributes to 52.3% of the variance of the total forecasted extra revenue (row 1, column 4). Therefore, current research is ongoing for selecting *Zea mays* cultivars based on their optimal biomass and biogas production potential. As such, energy maize and biogas production represent a new branch of agriculture. Prices of fodder and energy maize have a correlation of 0.5 in the integrated model, resulting in the relative large importance (12%) of the price of fodder maize. For the integrated model to have a Prob(R>0) ≈90%, it suffices that both prices have a most likely value of € 30 ton^{-1}. When optimizing both models separately, prices have to be determined as in§3.3.3. The price of green certificates is an important variable in explaining the variance in the income resulting from the digester (column 3, row 4). In the integrated model, it is still clear that subsidies will continue to have a large impact on the rentability of a phytoremediation project. Prices of electricity are very volatile, given the rather important variance of the income explained by this variable (11%), contracts with electricity distributors might offer guarantees.

4. Conclusion

From literature, we find that most effort for now has been invested in optimizing the technical, agronomic and biological aspects involved in phytoremediation for it to be become a real-scale working technology (Chaney *et al*., 1997; Garbisu and Alkorta, 2001; Vassilev *et al*., 2002). In case of large areas, although only moderately polluted with heavy metals, the economic aspect indicates the opportunity for the low cost phytoremediation technique combined with energy production. The investment in a digester can be done by a group of cooperating farmers. Cooperation between farmers can be successful, as already shown in Denmark (Raven and Gregersen, 2007). According to our analysis, the minimum number of farmers to have a fair chance that the digesting is profitable is 15, as economies of scale apply for the CHP engine from thereon.

Pessimistic scenarios show the importance of the level of the maize price, operational subsidies in the form of Green Current Certificates and the selling price of electricity produced. Changing each of them with 10% *(cet. par.)*, renders the installation unviable. Each of them is determined by the market and as such not under control of the farmer. However, given current prices of fodder maize, the farmer can decide whether he will sell his energy maize at a given calculated price to a digester and whether or not he is prepared to take part in the digestion project. Concerning the contaminated digestate, to reach an almost certain extra income resulting from digestion, it is necessary to find a useful use for the net heat. Not doing this will render the installation unviable.

Collecting all the influences from the analysis in part I (the farmer only grows energy maize, see the previous article) and part II (concentrating on the extra farmer's income from digestion), the simultaneous influence of all the determinants is considered. The total average extra revenue for the farmer (i.e. from both growing energy maize and performing digestion) amounts to € 191 $ha^{-1}y^{-1}$, which means an increase of 17% compared to his current income. Moreover, the probability that this extra income is positive is 90% when he grows energy maize instead of fodder maize and simultaneously exploits the digester in cooperation with other farmers. As such, ecological benefits stemming from phytoremediation go hand in hand with economic benefits for the farmer.

For now this study looked at the economic viability of phytoremediation by energy maize. However, as already mentioned in the course of the analysis, acceptability of phytoremediation and the choice for a certain crop does not only depend on economics but also on acceptance of this crop, not only by the farmer, but also by the surrounding community. Other aspects to be considered are the extraction capacity of the chosen crop, further use of the crop together with fitting in energy maize in a mix of remediating crops. This analysis already touched the aspect of conversion of energy maize into energy by digestion, but other crop-conversion-energy routes remain possible, resulting in different net energy production and consequently in different CO_2-equivalents avoided.

Appendix

A. Calculation of the yearly extra income per hectare

The extra yearly income for the farmer is obtained by recalculating the NPV to an annuity, i.e. a yearly constant cash-flow which, after discounting, would again lead to the NPV. This annuity is calculated by multiplying the NPV with an annuity factor AF in Eq. 3 (i = discount rate = 6%). The annuity is then divided by the number of hectares, resulting in the extra yearly income (over 20 years) from the digestion activity.

$$\mathrm{AF} = \frac{i}{1-(1+i)^{-n}} \qquad \text{(Eq. 3)}$$

We use this formula for the calculation of the capital cost of the engine and digester (Table 2) and for calculation of R. Given i = 6% and n = 20, AF= 0.087;

Capital cost of digester (engine is calculated similarly):

2,676,000*AF= € 233,305

Yearly extra income in deterministic case:

$$\frac{(266{,}271 * \mathrm{AF})}{15 * 20)} = € \ 77.4 \ \mathrm{ha}^{-1}$$

B. Digester and engine: dimension and investment costs

Based on the assumption that each farmer grows energy maize on 20 ha, with a yield of 60 tons fresh matter per hectare, the dimension of the digester will only depend on the number of farmers that cooperate, The dimension can be calculated according to the following formula (Lemmens *et al.*, 2007; Timmerman *et al.*, 2005).

$$Dig = (H \cdot mE)/365 \cdot Res \qquad \text{(Eq. 4)}$$

With: *Dig*: dimension of the digester (m^3)

H: number of ha (= number of farmers (*N*) $\cdot$ 20 ha/farmer)

mE: yield of energy maize per ha

Res: residence time of the biomass in the digester (days)

If 15 farmers cooperate, the total biomass available is 18,000 tons FM per year. With a residence time of 38 days (dry digestion), a digester of 1,874 m^3 is needed. The number of farmers willing to start the cooperation or to deliver maize as a feedstock to the digester is important.

The life span of the digester is 20 years, with a degressive depreciation scheme and a zero end value (Murphy and McKeogh, 2006; Maeng *et al*., 1999). The investment costs of the specific installation (Table B1) used in this study come from Goossens (2007), personal communications with experts and own calculations. We will not assume ‘economies of scale’, as is also the case in Lemmens *et al.* (2007) and Timmerman *et al.* (2005). Generalisations should be made with caution as numerical values in literature differ largely due to different assumptions regarding the biomass used, the involved machinery, the included engine, the size of buildings, whether the farmer himself takes care of the construction, etc.

Table B1: Specific investment costs digestion installation

Digester parts	**Investment**	**Allocation variable**
Basic installation	97.50	€ ton^{-1} fresh material (FM) biomass
Dewatering installation	10.00	€ ton^{-1} FM biomass
Buildings	28.33	€ ton^{-1} FM biomass
Desulphurization	0.032	€ m^{-3} gas
Measuring, cooling	0.035	€ m^{-3} gas

The produced gas will be burned in a gas engine with heat recovery in a combined heat and power engine. Heat and electricity produced by the engine are calculated respectively as follows:

Heat produced = $mE \cdot H \cdot G \cdot EV \cdot n_{th}$ (Eq. 5)

Electricity produced = $mE \cdot H \cdot G \cdot EV \cdot n_e$ (Eq. 6)

With: $mE \cdot H$: total amount of biomass available (mE=60 tons per hectare, H= 20 ha $\cdot$ N)

G: energy value of biomass digested (190 m^3 gas ton^{-1} FM maize)

EV: energy value of gas produced (53% CH_4 assumed leads to 5.3 kWh m^{-3} gas)

n_e and n_{th}: electric and thermal efficiency of the engine (n_e = *41% and* n_{th} 43%)

In this paper, each participating farmer dedicates 20 ha to growing energy maize for the digester. The output of heat by the digester is therefore much larger than the demand by the local farmer. The approach in this paper is to consider the amount of biogas produced using the biomass offered by the group of farmers willing to engage in the phytoremediation project. Other demand for heat has to be sought, e.g. district heating, heating of a nearby hospital or swimming pool, and drying and/or processing the digestate. For electricity too, contracts have to be closed to deliver electricity to a swimming pool, a building with a large electricity demand, a factory, etc. or it can be put on the electricity grid. In this paper all net heat (i.e. after process use) is used to dry the digestate, all net electricity (i.e. after process use) is put on the grid. The dimension of the engine (Dim) in kWe can then be calculated (h_t: the theoretical working hours of the engine assumed per year (7,500 hours)):

$$Dim = Eq\ 5 / h_t \qquad \text{(Eq. 7)}$$

Investment costs (I_m) of the engine are calculated according to Stroobandt (2007) and Goossens (2007), based on data from specific cases, as follows:

$$I_m = (-386.1 * \ln(900) + 3{,}170.5) * 1.2 * Dim + \text{Inv elec wiring};$$

$$\text{in case } Dim > 900 \text{ kWe} \qquad \text{(Eq. 8a)}$$

$$I_m = (-386.1 * \ln(\text{Dim}) + 3{,}170.5) * 1.2 * Dim + \text{Inv elec wiring};$$

$$\text{in case } Dim < 900 \text{ kWe} \qquad \text{(Eq. 8b)}$$

The life span of the gas engine is 10 years, so a second investment is needed in year 11 to be able to perform the analysis over 20 years. Like the digester, the engine is degressively depreciated.

C. Combined Heat and Power Certificates

The support for exploitation coming from *CHPC* depends on several factors. The CHP system has to be ‘qualitative’, meaning that the Relative Primary Energy Savings (*RPE*) have to be larger than 0% for units smaller than 1 MW and larger than 10% for larger units. For small units this means that less primary energy should be used than when electricity and heat are produced separately. This is done by comparing the thermal and electrical efficiency of the engine used with European standard values, established in a Ministerial Decision, see equation 9 (Peeters, 2006). If this condition is fulfilled, then support (*RCHPC*) is given, calculated in equation 10. The issue of certificates is assured by the government during 10 years. After the fourth year the revenues out of certificates will be diminished as one assumes a loss of efficiency. Therefore, RCHPC is multiplied with X. The formula for X is given by equation 11 (Flemish Government, 2006).

$RPE = 1-1/(n_e /REF_e + n_{th}/REF_{th})$ (Eq. 9)

$RCHPC = [1/ REF_e + n_{th} /(REF_{th} \cdot n_e) – 1/ n_e] \cdot Dim \cdot h_w \cdot (1-p_e) \cdot PCHPC/1{,}000$ (Eq. 10)

$X=100 \cdot (RPE-0.2(T-48))/RPE$ (Eq. 11)

In equation 9, REF_e and REF_{th} are the European standard electrical and thermal efficiencies as found in the Ministerial Decision. In equation 10, Flemish reference efficiencies are used for calculating *RCHPC*. These are determined in a Decision of the Flemish Government (Flemish Government, 2006). The price of the certificates (*PCHPC*) is minimum € 27 MWh^{-1} and maximum € 45 MWh^{-1}. In equation 11, T = total months after the past year, in the fifth year for example, T= 60.

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TABLE 1: RATE OF BIOGAS PRODUCTION COMPARED FOR UNPOLLUTED AND HEAVY METAL CONTAMINATED WATER HYACINTH, WATER CHESTNUT, CHANNEL GRASS AND SLUDGE FROM LITERATURE

Singhal and Rai (2003)	Water hyac. unpolluted	Water hyac. in 20% paper mill effluent	Channel grass unpoll.	Channel gr. in 20% paper mill effl.
(cc±SE/100 g DM/day) time interval 9-12 days	153.3±1.17	233.3±4.7	150±4.74	213.3±4.7
Verma *et al*. (2006)	Water hyac. Unpoll.	Water hyac. in 20% effl. (Cu and Cr)	Water chestnut unpoll.	Water chestn in 20% effl. (Cu and Cr)
(cc±SE/100 g DM/day) time interval 8-12 days	158.6±2.5	189.2±1.85	111.5±2.2	139.5±2.25
Wong and Cheung (1995)	Raw sludge	Sludge with Cr (80 mg l^{-1})	Sludge with Cu (150 mg l^{-1})	
(mg l^{-1} volatile solids) daily interval	11.37	8.68	10.41	

TABLE 2: CASH FLOW IN YEAR 1 AND NPV FOR THE DIGESTER, GIVEN MOST LIKELY DETERMINISTIC VALUES FOR THE VARIABLES

		Absolute value (€)	**Average %**
(1)	**Total cash flow in**	**1,624,108**	**100%**
	Electricity sold to the grid	523,190	32%
	Opportunity value electricity	0	
	Green Current Certificates	735,735	45%
	Opportunity value heat	0	
	Combined heat and power certificates	365,184	23%
	Other support	0	
	Digestate	0	
(2)	**Total cash flow out**	**1,319,422**	**81%**
	Capital cost digester	233,305	14%
	Capital cost CHP engine	109,823	7%
	Maintenance CHP	143,289	9%
	Maintenance digester	38,700	2%
	Feedstock (energy maize), incl. transport	552,438	34%
	Ensiling energy maize	36,000	2%
	Digestate cost	97,687	6%
	Diverse costs	108,180	7%
(1)-(2)	**Cash flow in - Cash flow out**	**304,686**	**19%**
(3)	**NPV over 20 years** (discount rate of 6%)	**266,272**	

TABLE 3: BASE CASE VALUE RANGES FOR THE VARIABLES DETERMINED BY A MOST LIKELY VALUE ± 10%

Variables	Minimum value	Most likely value	Maximum value
(1)	(2)	(3)	(4)
Number of farmers (*N*)	13.5	15	16.5
Yield energy maize per ha (*mE*) (ton ha^{-1})	50	60	65
Price energy maize per ton (*P*) (€ ton^{-1})	27	30	33
Price energy maize per ha (€ ha^{-1})	1,350	1,800	2,145
Transport cost maize (€ ton^{-1} ha^{-1})	0.45	0.5	0.55
Price CHP Certificates (€ MWh^{-1})	36.45	40.5	45
Price Green Current Certificates (€ MWh^{-1})	101.25	112.5	125
Opportunity value heat (€ MWh^{-1})	24.75	27.5	30.25
Price electricity sold to the grid (€ MWh^{-1})	72	80	88
Disposal cost digestate (€ ton^{-1})	4.5	5	5.5

TABLE 4: DETERMINATION OF IMPORTANT VARIABLES IN CALCULATING THE AVERAGE EXTRA INCOME PER HECTARE PER YEAR (*R*)

Variable	Contribution to the variance of *R*
Price Green Current Certificates	38.8%
P(energy maize)	-24.9%
Price electricity sold to the grid	23.6%

TABLE 5: EFFECT OF A CHANGE IN THE MOST LIKELY VALUE OF A VARIABLE (COL. 3) (*CETERIS PARIBUS)* ON AVERAGE *R* (COL.5) AND ON PROB(NPV>0) (COL.7) AND THE DIFFERENCE OF THESE OBTAINED VALUES WITH THE BASE CASE VALUE FOR *R* AND PROB(NPV>O) (COL.6 & 8)

		Most likely value			**Average extra revenue (*R*)**		**Prob(NPV>0)**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Variables	**Base case**	**Worse case**	**Diff (%)**	**Value (€ $ha^{-1}y^{-1}$)**	**Diff (€)**	**Value (%)**	**Diff (%pt)***
(1)	Price Green Current Certif. (€ MWh^{-1})	112.5	101.25	-10%	-79.3	-155.9	22.2%	-53.5%pt
(2)	Price energy maize (€ ha^{-1})	30	33	+10%	-63.2	-139.8	28.0%	-47.7%pt
(3)	Price electricity sold to the grid (€ MWh^{-1})	80	72	-10%	-49.2	-125.8	31.6%	-44.1%pt
(4)	Price CHP Certif. (€ MWh^{-1})	40.5	30	-25%	-38.2	-114.8	35.6%	-40.1%pt
(5)	Number of farmers	15	10	-33%	-24.8	-101.4	40.7%	-35%pt

*%pt= percentage point

TABLE 6: EFFECT OF USING HEAT FOR DRYING DIGESTATE ON THE EXTRA INCOME PER YEAR AND PER HECTARE*(R)*

% of heat used for digestate	**% of heat used in process**	**% of heat sold at 27.5 € MWh^{-1}**	**% of heat with certificates**	***R* (€ ha^{-1} y^{-1})**	**Prob(NPV>0) (%)**
25%	4.1%	71.9%	71.9%	271.4	99.5
38%	4.1%	57.9%	57.9%	143.7	90.7
50%	4.1%	45.9%	45.9%	23.6	58.0
75%	4.1%	20.9%	20.9%	-232	1.7

TABLE 7: CALCULATION OF THE MAXIMUM ENERGY MAIZE PRICE (COL.3) AND OF THE AVERAGE YEARLY REVENUE PER HA (COL.5) SUCH THAT PROB(NPV>0) ≈ 90% GIVEN THE BASE CASE- AND NEGATIVE SCENARIOS

	Variable	Most likely value (given)	Max Price energy maize (calculated)	Prob(NPV>0) (%)	***R*** (€ ha^{-1} y^{-1})
	(1)	(2)	(3)	(4)	(5)
(1)	Base Case	See Table 3	28.7	90%	134.6
(2)	Price Green Certif.	101.25	25.5	90%	123.5
(3)	Price CHP Certif.	30	26.1	90%	127.6
(4)	Price electr. grid	72	26.1	90%	128.2

FIGURE 1: DETERMINATION OF ENERGY MAIZE PRICE, GIVEN A FODDER MAIZE YIELD OF 50 TON FM, TO HAVE AN ALMOST CERTAIN POSITIVE EXTRA INCOME (PROB(*R*>0) ≈ 90%), AND DIFFERING ACCORDING TO THE RELATIVE YIELD OF ENERGY MAIZE TO FODDER MAIZE (*ME/MF*) AND FODDER MAIZE PRICE

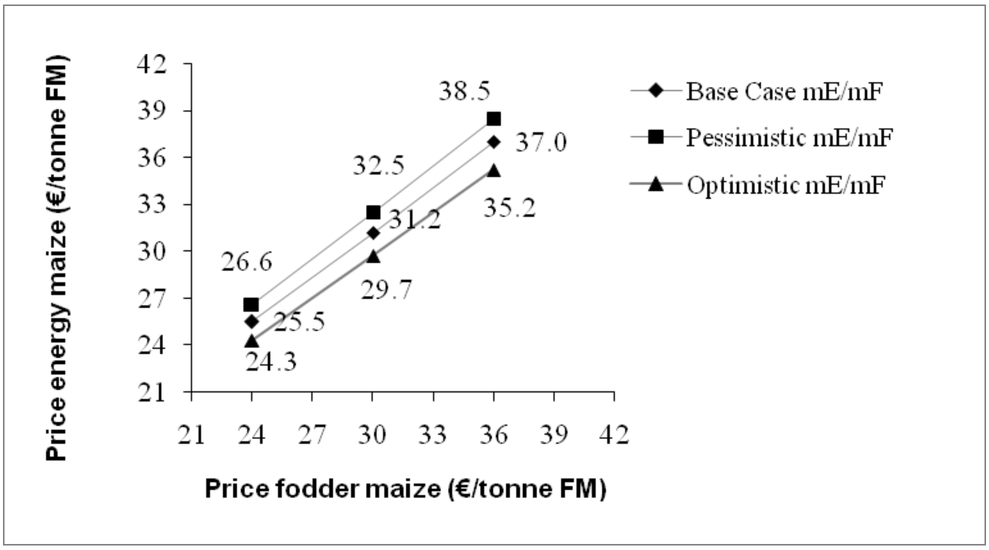

TABLE 8: INTEGRATION OF PART I AND PART II: CONTRIBUTION OF THE VARIABILITY OF THE VARIABLES TO THE VARIANCE OF THE TOTAL EXTRA REVENUE OF THE FARMER *(R)*

		Part I: income from selling energy maize	**Part II: income from digestion**	**Integration Part I and II: total extra income**
	(1)	(2)	(3)	(4)
(1)	Yield energy maize	81.3%		52.3%
(2)	Price energy maize	13.4%	-24.9%	
(3)	Price fodder maize	-4.9%	-6.5%	-12.2%
(4)	Price Green Current Certif.		38.8%	19.5%
(5)	Price electricity to grid		23.6%	11.4%
(6)	Extra income for the farmer *(R)* (€ $ha^{-1}y^{-1}$)	113.8	76.6	191.4
(7)	Probability of a positive impact on the farmer's income	82.6%	75.7%	89.0%