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Investigation of the Influence of Plant Capacity on the Economic and Ecological Performance of Cassava-based Bioethanol

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In this work, economically optimal capacities for cassava-to-ethanol plants are determined by using a nonlinear optimization approach. Both economies of scale and required transportation distances are approximated with appropriate functions to identify optimal capacities with regard to the required investment, input and output prices and the available amount of cassava in proximity of the envisioned plant. Usage of high cassava yields on agricultural soils is expected to result in significantly higher returns on investment (ROI), but the use of such soils may endanger food production. The use of marginal lands does not have this side-effect to the same extend, but is associated with higher transportation-related greenhouse gas emissions due to longer expected transportation distances. Therefore, in addition to identifying optimal production capacities for a number of scenarios, the investigation also aims at quantifying the effect of cassava cultivation on marginal lands in regard of the economic and ecological performance of cassava-based ethanol production.

1. Cassava from marginal lands as input material for bioethanol production

Both environmental concerns associated with the emission of carbon dioxide into the atmosphere and economic considerations associated with relatively high oil prices continue to promote the use of biofuels (Ceclan et al., 2012). In contrast to other renewable energies, however, the market share of biofuels remains almost negligible in all but a small number of countries worldwide. Although economies with sizable biofuel production include the US, the EU and Brazil, the policies to advance the use of biofuels are contested on a regular basis even in these economies. Biofuels may arguably be competitive on the fuel market as a function of the climate and economy of the countries in question (Schmitz, 2009). In any case, the currently prevalent 1st generation biofuels are being criticized for two major disadvantages: Firstly, they compete for arable soil, which means that their increased production may lead to a deterioration of food supply security. This is especially relevant in places where a high percentage of the population's income is spent on alimentation.

Secondly, the ecological performance of biofuels, as determined in Life Cycle Assessments (LCA) is a matter of dispute as well. A comprehensive LCA has to take numerous ecological effects into account, including GHG emissions of the whole field-to-wheel system, land use change effects, water consumption and several effects on the soil such as eutrophication or nutrient withdrawal (Azapagic and Stichnothe, 2011). Generally speaking, the production of biofuels is associated with disadvantages that may potentially overcompensate the beneficial effects. 2nd generation biofuels are designed to avoid using crops which might also serve as food, but have so far been found to lack economic competitiveness due to the costs of the required advanced conversion processes. A different approach to produce biofuels is to use plants that can be grown on so-called marginal land. Marginal land, sometimes also referred to as wasteland, is characterized by poor soil and therefore produces lower yields per hectare than higher-rated agricultural

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soils. Defining soils as “marginal” is controversial, however, as local groups may nevertheless depend on such lands “for [their] livelihoods” (Cutola et al., 2008).

Due to the high achievable bioethanol yields per hectare, cassava is seen to be increasingly favoured for the production of biofuels from marginal land. Originating from South America, cassava today serves as one of the most significant sources of nutrition in tropical regions throughout the world. The reasons for the successful introduction of the plant in other tropical regions were the same that make cassava a candidate for biofuel production from marginal lands at present, as cassava “tolerates acid soils, periodic and extended drought and defoliation by pests” (Hillocks et al., 2002). As cassava can be used for “food, feed and industrial processes”, growing cassava on marginal land could contribute to each of the three purposes (Hillocks et al., 2002). Cautious and well-reflected decisions, which take both the potential effects/impact on food prices and also the danger of direct and indirect land use changes into account, are therefore in order when considering the use of cassava in bioethanol production.

For the purpose of this investigation it is assumed that marginal lands are available for biofuel production to a limited extend of up to 10 % of a given area without compromising food security or inducing land-use changes. As this assumption has potentially grave consequences for the investigation as a whole, the availability of marginal land will be thoroughly examined in the sensitivity analysis.

2. Nonlinear approximation of optimal cassava-to-ethanol plant capacities

Due to containing highly fermentable sugars, cassava is a feasible input material for bioethanol production (Hillocks et al., 2002). As yields on marginal lands may however be significantly lower than elsewhere, the effects of cassava availability on bioethanol production costs have to be investigated. In order to determine whether a given area of marginal land can be used for the economically competitive and environmentally sound production of bioethanol, optimization models can be applied. For a given set of parameter values, optimization models as described by Lauven (2011) can help to determine economically optimal plant capacities (x, in $t_{ethanol}$/y), corresponding ethanol production costs and transportation-related greenhouse gas (GHG) emissions.

Economic advantageousness can be measured by approximating the prospective return on investment (ROI) or the net present value (NPV) of a cassava-to-ethanol plant. A simplified NPV calculation, which returns the prospective added value of an investment compared to a required rate of return, can be used to estimate the economic performance of plant investments (Ng et al., 2012). Such an NPV calculation returns an absolute value, however, which makes it difficult to adequately compare results for significantly different capacities. As the ROI result, by contrast, is given relative to the estimated plant investment, ROI maximization was chosen as the objective function in this study.

When effects induced by capacity changes are investigated, the approximation of several key cost components requires the use of nonlinear functions. This is true for both investment-related and transportation-related costs, which are in nonlinear correlation with plant capacity. For investments, and therefore for the investment-related costs needed to determine production costs, the growth for different capacities is usually approximated by using an economies of scale approach (Sinnot, 2009).

Table 1: Parameter values

Item	Value	based on
Factor for investment-related costs (f)	0,1817	Peters 2003, BOT 2013
Base value for economies of scale (a)	60,000 $/t/y	NNT 2006
Ethanol price (b)	760 $/t	Nguyen 2008
Cassava Price (c)	40 $/t	Nguyen 2008
Variable transportation costs (v_1)	0.12 $/(t·km)	Kerdoncuff 2008
Variable GHG emissions (v_2)	147.5 g_{CO2}/(t·km)	GEMIS 2000
Conversion ratio for fresh roots (θ)	6.6 $t_{cassava}/t_{ethanol}$	Nguyen 2008
Yield (ψ)	5 t/ha	Hillocks 2002
Share of total area (λ)	4 %	own assumption
Plant capacity (x)	optimization variable	-

$$C_2 = \left(\frac{S_2}{S_1}\right)^n \cdot C_1 \tag{1}$$

Where
C_i = Capital costs of project i
S_i = Capacity of project i

The index n was assumed to be 0.67 for the purpose of this investigation. Table 1 shows the most important parameters used for the optimization calculations. While marginal investment-related costs exhibit decelerated growth relative to capacity, transportation distances grow more rapidly. As both variable transportation costs and transportation-related greenhouse gas emissions depend on the average transportation distance, distance-based approaches can be used for an estimation of the two. Under the assumption of a circular cassava supply area surrounding the plant, distances can be approximated from plant capacity by using a factor with an exponent of 1.5 (Wright and Brown, 2007). Based on this, calculation methods were developed by Searcy and Flynn (2009) as well as Lauven (2011) to directly approximate transportation costs for a given plant capacity (x). Due to the similarity of the model structure, the latter approach was used to approximate transportation costs from plant capacity.

$$c_{transport} = v_1 \cdot \frac{\theta^{1.5}}{\sqrt{\pi \cdot \psi \cdot \lambda}} \cdot x^{1.5} \tag{2}$$

The different development of these two cost items relative to plant capacity means that the resulting objective function is concave, as all other decisive items (sales and cassava-purchasing costs) are in a linear relationship with the plant capacity. Concave functions have exactly one (and therefore global) optimum, which means that there is one optimal capacity that maximizes the return-on-investment (ROI). For any optimal capacity, the corresponding average transportation distances determine both the variable transportation costs and the transportation-related GHG emissions. In order to determine an optimal capacity for a given region or scenario, values for a number of decisive parameters must be determined or approximated. Under the assumption that the entire cassava-to-ethanol plant's production can be sold, sales can be calculated by multiplying the plant capacity (t/y) with the expected ethanol price ($/t). In a manner similar to the calculation of sales, the plant's cassava purchasing costs can be approximated by multiplying cassava prices (c) with the required amounts of cassava ($\theta \cdot x$).

The calculation of investment-related costs requires knowledge of two other parameters: The base investment (a), which is multiplied with the capacity $x^{0.67}$ to approximate the required investment for a plant with a capacity of x, and the factor for investment-related costs (f). The factor f contains several cost items that are assumed to grow proportionally with the required investment (Vogel et al., 2008). These cost items include the annual depreciation (6.67 % in case of linear depreciation over 15 y), operating costs (assumed to be 8 %) and a term to represent the effects of inflation (around 3.5 % in Thailand in 2010/2011, BOT 2013).

A final set of parameters includes some decisive values associated with the availability and transportation of cassava. Variable transportation costs and GHG emissions must be determined for a given sort of transport vehicle, to be multiplied with the average transportation distance. The determination of this distance, in turn, requires assumptions concerning the cassava yield and the share of cassava fields relative to the total area of the region in question. The parameter values shown in Table 1 were assumed to be applicable for a cassava-to-ethanol plant in Thailand.

The complete objective function of the optimization model, g(x), includes ethanol sales, cassava purchasing costs, investment-related costs and transportation costs. As the sum of these is divided by the initial investment ($a \cdot x^{0.67}$) to determine the ROI, this results in the following Eq(3):

$$g(x) = \frac{(b - c \cdot \theta)}{a} \cdot x^{0.33} - f - v_1 \cdot \frac{\theta^{1.5}}{a \cdot \sqrt{\pi \cdot \psi \cdot \lambda}} \cdot x^{0.83} \tag{3}$$

3. Results and Discussion

If the objective function is maximized with the parameter values shown in Table 1, an optimal plant capacity of 329,396 t/y is determined. This is a relatively large but realistic capacity in the cassava-to-ethanol context. The investment would result in a ROI of 14.9 % and transportation-related GHG emissions of 10.75 g of CO_2 per MJ of ethanol. These GHG emissions are in line with similar publications about cassava-to-ethanol (Liu, 2013), although the consideration of marginal lands could be expected to lead to higher GHG emissions from transportation.

When investigating the influence of the parameters on the optimal solution, assuming differing investment-related costs is the only parameter change that has no influence on the optimal capacity whatsoever. Increasing the corresponding factor f merely results in a reduction of the ROI of equal proportions. For moderate changes in the parameter values of up to 25 %, the optimal capacity changes shown in Figure 1 result.

Among the most interesting parameters in the context of this investigation are the cassava yield and the share of a region's total area used for cassava cultivation (assuming that all cassava serves as input material for the bioethanol plant). While yields in excess of 20 t/ha are achieved in India, yields on marginal lands will be significantly lower. Yields as reported from Cambodia in the late 1990s (around 5 t/ha) were used as an approximation for marginal lands, as these were the lowest reported in Asia at the time (Hillocks, 2002). As these were nevertheless encountered on agricultural soils, the unknown yields on marginal lands demand further investigation and attention. At this point, it should be noted that as long as the cassava availability in a given area, defined as the product of cassava yield and share of cassava cultivation area, remains the same, so do the optimal plant capacity and the corresponding ROI. In other words, from an economic point of view, lower yields can be compensated by devoting a larger area to cassava production and vice versa. If cassava cultivation is limited to 10 % of a given area to avoid endangering food supply or inducing land use changes, this means that yields on these lands must be at least 2 t/ha in order to achieve the ROI of 14.9 % as shown above.

An investigation into the effect of parameter changes on the optimal plant size reveals that while changes in the assumed investment-related costs have no effect whatsoever, the cassava availability parameter shows a clearly linear effect on the optimal capacity.

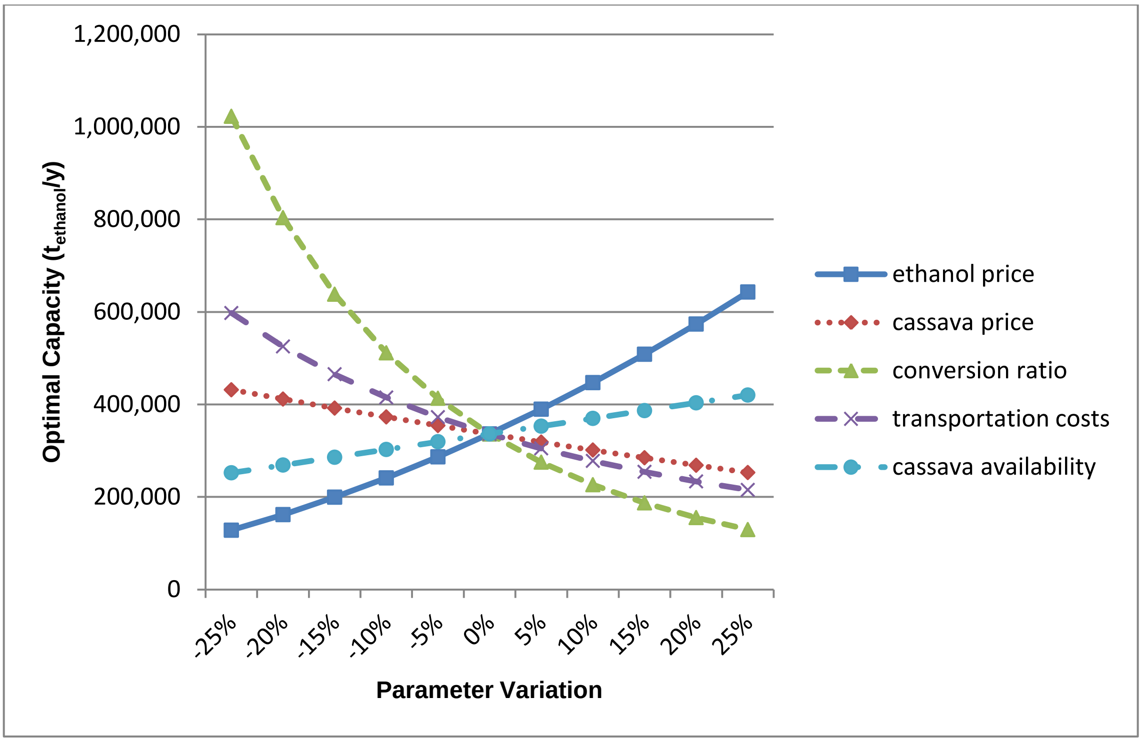

Figure 1: Optimal capacity sensitivity analysis

Figure 1 illustrates the fact that improvements of the cassava-to-ethanol conversion ratio (i.e. lower ratios) have the greatest leverage on optimal plant capacities. As improvements in this field lead to lower cassava transportation requirements and costs, it is consequential that capacities and ROIs increase significantly if the conversion ratio improves. If the conversion ratio was 7 instead of 6.6, as assumed by Liu (2013), the optimal capacity would be about 25 % lower. As this would also result in a negative ROI of about -10 % under the other assumptions summed up in Table 1, achieving a low conversion ratio is crucial for the economically successful operation of the plant.

The second-most important determinant of the optimal plant size is the ethanol price. This is a remarkable finding in itself, as several researchers have attempted to determine optimal bioenergy plant capacities with similar approaches without considering the product value (Wright and Brown, 2007) and later (Searcy and Flynn, 2009). In general, it can be concluded that higher product values increases not only the prospective ROI but also the optimal capacity of the plant.

Compared to the impacts of conversion ratio and ethanol price, both the input cassava price and the variable transportation costs have weaker, but nevertheless significant effects on the optimal plant capacity. Especially with regard to transportation costs, it has to be kept in mind that deviations in literature are relatively pronounced in percentage terms. For different kinds of biomass, findings by Kerdoncuff (2008) deviate by as much as 100 %. Compared to the other parameters, transportation costs are therefore relatively volatile and may significantly affect the optimization results in spite of the smaller effects that can be seen in Figure 1.

After a decision concerning the plant capacity has been made and construction of a plant has begun, parameter values can still change or turn out to be different than expected. Figure 2 shows how great the effect on the expected ROI would be if parameter values changed, but the plant capacity remained fixed. Compared to the previous investigation with variable plant capacity, it is apparent that the conversion ratio plays a considerably less prominent role.

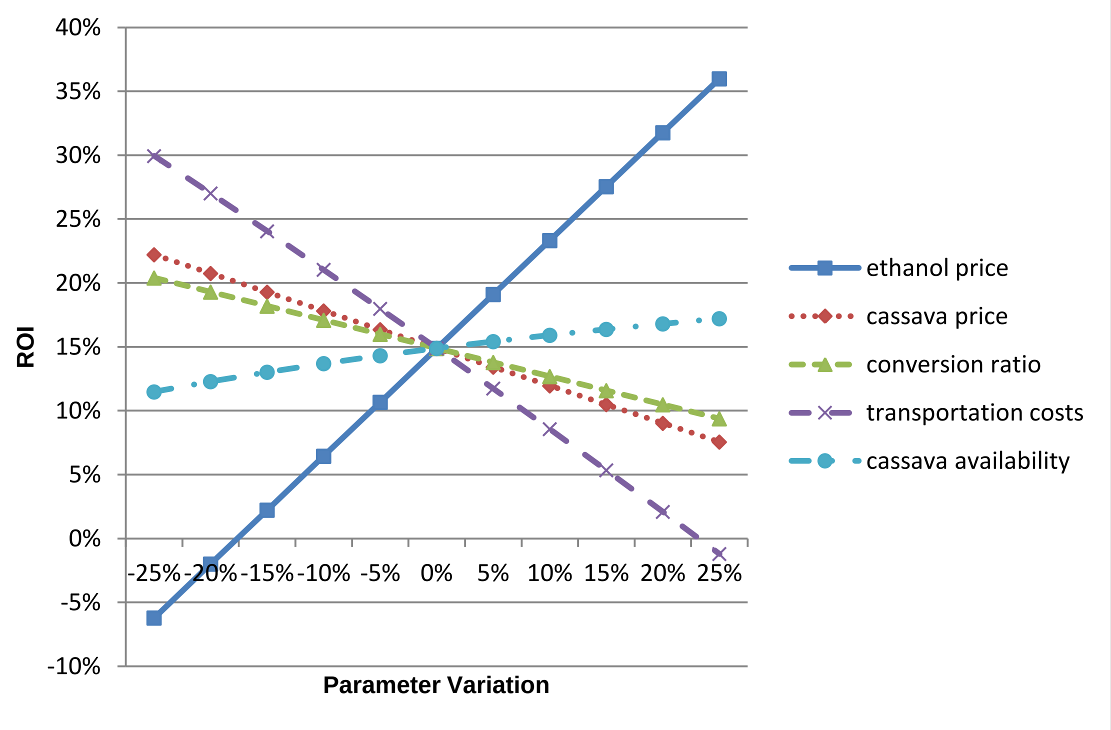

Figure 2: ROI sensitivity analysis for a cassava-to-ethanol plant with a fixed capacity of 336,040 $t_{ethanol}$/y

By contrast, transportation costs become the second most significant parameter. A 25 % deterioration of either ethanol price or transportation costs is sufficient to reduce the ROI from 14.9 % to below zero.

Cassava availability can be expected to be uncertain, as the marginal lands in question may be found to serve other, competing purposes. However, both sensitivity analyses show a relatively low impact for cassava availability and for the cassava price on the plants optimal capacity and ROI. Therefore, unfavourable changes on the input side appear to be less crucial than the use of an efficient technology and the value of the plant's products.

4. Conclusions and Outlook

An economically viable production of bioethanol from cassava cultivated on marginal lands is per se possible. Assuming that the parameter values presented in Table 1 are sufficiently close to reality, an economically viable cassava-to-ethanol plant with a ROI about 15 % would require marginal lands with a yield of at least 2 t/ha if 10 % of the area in question were available for cassava cultivation. In such a case, however, careful attention would have to be paid to the current usage of these marginal lands by the rural population. The optimal capacity and economic performance of such a plant depend on several parameters, of which the conversion ratio and the ethanol price are the most crucial. Research to improve the conversion ratio by enhancing the efficiency of the conversion technology is therefore a promising way to meet several ends: The usable energy from a given amount of agricultural soil increases, transportation-related costs and greenhouse gas emissions are reduced and the economic performance of the cassava-to-ethanol plant is improved. As the achievable ethanol price depends on government regulation in several countries, price guarantees may be a potent measure to reduce the risk of cassava-to-ethanol plants and therefore improve the incentives for firms to implement bioethanol plants using cassava as input feedstock. In the context of cultivating cassava on marginal lands, the result that cassava availability has a relatively limited effect on both the optimal capacity and the prospective ROI is an encouraging sign, as it means that the plant’s profitability is relatively robust with regard to changes in land use or competing uses for the lands in question.

In the future, the generic optimization approach described in this paper is to be extended to become more suitable for the analysis of biofuel plants at specific plant locations. This can be achieved by devising more detailed functions for biomass logistics and by including data from geographic information systems into the optimization approach.

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