Renewable Energy 89 (2016) 1–11

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Economic optimization of feedstock mix for energy production with biogas technology in Germany with a special focus on sugar beets – Effects on greenhouse gas emissions and energy balances

Sebastian Auburger [a, *], Anna Jacobs [b], Bernward Märländer [b], Enno Bahrs [c]

[a] University of Hohenheim, Department of Farm Management (410b), 70593 Stuttgart, Germany
[b] Institute of Sugar Beet Research, Holtenser Landstrasse 77, 37079 Göttingen, Germany
[c] University of Hohenheim, Department of Farm Management (410b), 70597 Stuttgart, Germany

ARTICLE INFO

*Article history:*
Received 30 April 2015
Received in revised form
16 October 2015
Accepted 16 November 2015
Available online xxx

*Keywords:*
Linear programming
Spatial modeling
Sugar beets
Silage corn
Biogas

ABSTRACT

Power production from biogas is quite common in Germany and other parts of the world. German biogas production, in particular, primarily uses silage corn as feedstock which is unpopular with the society because of the negative side effects. Sugar beets could be an alternative. This paper maps the aggregated results concerning the greenhouse gas (GHG) emissions and energy balances of power production from different energy crops at national level based on field experiments and all biogas plants registered in Germany. The regional feedstock production costs integrated into the objective function of a plant specific linear optimization model were calculated based on regional production circumstances and district specific yields. Different scenarios with e.g. a fixed share of sugar beets in biogas plant feedstock mix as well as yield increases due to biological and technical progress of silage corn and sugar beets were compared to a business as usual scenario in terms of their effects on GHG emissions and energy balances of power production. The results demonstrated that the GHG emissions and energy balances depend on regional production circumstances. Furthermore, forcing sugar beets into feedstock mix resulted in generally higher GHG emissions and deteriorated energy balances.



## 1. Introduction

The promotion, establishment and subsidization of renewable energies worldwide are mainly justified by their low greenhouse gas (GHG) emissions [1], positive net energy balances and potential for satisfying future energy demand [2] in contrast to fossil energy sources. Hence, our approach in this study focused on GHG emissions and energy balances because both are key indicators for a sustainable energy supply. By the end of 2013, more than 25% of the gross electricity use and 9% of the heat consumption in Germany were provided by renewable energy sources [3]. Renewable energy is predicted to account for 80% of the electricity production in Germany by 2050 [4]. One part of this energy mix is the power production in biogas plants (BGPs) with combined heat and power units (CHP) which are regarded as a technology that protects the environment and helps to avoid climate change [5]. In the context of GHG emissions and analogous to EU biofuel regulations, in the future, a certain mitigation potential may be required to receive subsidies for power production based on biogas [6]. For agricultural BGPs, GHG emissions and energy balances depend highly on the feedstock used [7,8] and, in the case of energy crop production, on the regional production circumstances [9,10].

However, energy crops, especially silage corn (SC), are currently the most-used feedstock in BGPs in Germany [11], primarily because of their low production costs [12,13]. In particular, production of SC faces accusations of negative side effects: the risks of decreasing biodiversity [14], increasing soil erosion [13] and decreasing social acceptance of the biogas technology [15] are discussed in the context of increased SC production in Germany. Sugar beets (SB) could be a potential supplement to reduce the mentioned negative side effects of BGPs, especially as they are a fast degradable feedstock [16]. Given that the operations of existing BGPs are bound to their current physical location and that further technological development of BGPs in Germany is unrealistic [17], the potential for reducing the GHG emissions associated with biogas production lies in digesting energy crops of a reduced input-

* Corresponding author.
*E-mail address:* sebastian.auburger@uni-hohenheim.de (S. Auburger).

http://dx.doi.org/10.1016/j.renene.2015.11.042
0960-1481/

**Acronym**

| | |
|---|---|
| B | Scenario: Breeding scenario with yield improvement for SC and SB |
| BAU | Scenario: Business as usual, baseline scenario |
| BGP | Biogas plant |
| CHP | Combined head and power unit |
| DM | Dry matter |
| EU | European Union |
| FA | Feeding activity within the linear programming model |
| FM | Fresh matter |
| FU | Functional unit |
| GHG | Greenhouse gas |
| GHGmin | Scenario: Minimization of GHG emissions |
| GWP | Global warming potential |
| LCA | Life-cycle Analysis |
| MCF | Methane conversion factor |
| PC | Variable Production costs |
| Powermax | Scenario: Maximization of electrical power generation |
| REA | German Renewable Energy Act |
| SB | Sugar beet |
| SBimp | Scenario: At least 25% sugar beet in feedstock ratio |
| SC | Silage corn |
| SCmax | Scenario: Maximum of silage corn in feedstock mix |
| WPWW | Winter wheat as whole plant silage |
| WW | Winter wheat as grain |

intensity. For example, SB production is characterized by low fertilizer input [18] which implies that it has an economic and environmental advantage [19]. In general [20], found that high yields with low environmental impacts could be obtained and [21] reported high methane yields and high energy outputs for SB. The joint project "The sugar beet as an energy crop in crop rotations on highly productive sites — an agronomic/economic systems analysis" evaluates different crop rotations in Germany with a special focus on SB as a feedstock for BGPs [22]. Therefore, the following hypotheses are to be verified in our study:

1. The GHG emissions and energy balances of power production based on biogas in Germany depend on the regional production circumstances of the different energy crops.
2. Integrating SB into the feedstock mix of BGPs results in lower GHG emissions and improved energy balances of biogas production.

We thereby propose an economic/ecologic model which is described in the following section.

## 2. Materials and methods

### 2.1. Overview of model setup

Our model contained 7909 geocoded BGPs in Germany and comprise four major sub-models which are executed for each BGP successively and separately with regional input variables (Table 1). (i) The feedstock production costs per ton were calculated as variable costs considering the regional production circumstances and the BGP size. (ii) The feedstock input was optimized by linear programming which included a minimization of feedstock costs subject to the feeding restrictions based on the German Renewable Energy Act (REA) and on the biological restrictions of fermentation. Finally, two ecological indicators for the environmental impact of biogas production in Germany were assessed as the GHG emissions (iii) and the energy balances (iv) based on results of optimized feedstock choice for each BGP and then further aggregated on a district and national level.

For calculating GHG emissions and energy balances, we followed the ISO 14040:2006 approach for conducting a partial life cycle analysis (LCA). Fig. 1 shows the system boundaries of our cradle-to-grave approach in terms of the GHG emissions and energy balances.

The GHG emissions associated with construction and demolition of BGPs were not considered because they can be regarded as having a negligible impact [9,23–26]. The biogas digestates associated with the respective energy crops were completely recycled into the energy crop production systems. Therefore, no outputs concerning biogas digestates were considered. Given that all of the considered BGPs were operated with CHPs by assumption, we considered only the external heat use as a heat output [27]. Hence, the energy input needed for heating the digesters (internal heat use, see below) was not considered separately. Since manure was assumed to be available at the BGP sites, the GHG emissions and energy inputs associated with the manure supply were not considered [27,28].

The regional GHG emissions and energy inputs of energy crop production were calculated by using the GHG emissions coefficients of ENZO2 [29], a GHG calculator for biofuels based on agricultural production systems that is officially accepted by the German government [30]. Yields of energy crops are derived from Ref. [31] as an average value at the district level (2008–2012). In order to evaluate future developments and policy options against a baseline scenario, we calculated the following scenarios (Table 2).

**Table 1**
Overview of the sub-models, input parameters and model output on biogas plant (BGP) level.

| Sub model | | Model parameters | Model results |
|---|---|---|---|
| i | Calculation of regional feedstock production costs | Local yields and average field size, size of the BGP ($kW_{el}$) | Feedstock production costs in Euro $t^{-1}$ for silage corn, sugar beet, winter wheat as whole plant silage and grain |
| ii | Linear model of optimized feedstock mix | Feedstock production costs in Euro $t^{-1}$ (target function), full load hours of the CHP, size of the BGP ($kW_{el}$), local ratio between cattle and pig numbers, manure input bonus | Feedstock mix in $t^{*}y^{-1}$ as the proportion of silage corn, sugar beet and winter wheat as whole plant silage and grain |
| iii | GHG emissions | Feedstock mix in t $y^{-1}$, GHG emissions of feedstock production, GHG emissions of BGP operation | GHG emissions of power production in $kgCO_2eq\ kWh_{el}^{-1}$ |
| iv | Energy balance | Feedstock mix in t $y^{-1}$, energy consumption of feedstock production, energy demand for BGP operation | Net energy output of power from biogas in GWh $y^{-1}$ and input–output-ratio as $MJ_{fossil}{}^{*}MJ_{biogas}^{-1}$ |