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Optimization of bioenergy yield from cultivated land in Denmark

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ARTICLE INFO

Article history:
Received 21 September 2009
Received in revised form
3 March 2010
Accepted 16 April 2010
Available online 14 May 2010

Keywords:
Bioenergy supply
Biomass feedstock
Cost minimization model
Landuse
Linear programming
Nitrogen load

ABSTRACT

A cost minimization model for supply of starch, oil, sugar, grassy and woody biomass for bioenergy in Denmark was developed using linear programming. The model includes biomass supply from annual crops on arable land, short rotation forestry (willow) and plantation forestry. Crop area distributions were simulated using cost data for year 2005. Five scenarios with different constraints, e.g. on food and feed supply and on nitrogen balance were considered focusing on: a) constraints as the year 2005, b) landscape aesthetics and biodiversity c) groundwater protection, d) maintaining current food and feed production, or e) on site carbon sequestration. In addition, two oil price levels were considered. The crop area distributions differed between scenarios and were affected by changing fossil oil prices up to index 300 (using 55$ per barrel in 2005 as index = 100). The bioenergy supply (district heating, electric power, biogas, RME or bioethanol) varied between 56 PJ in the "2005" scenario at oil index 100 and 158 PJ at oil index 300 in the groundwater scenario. Our simple model demonstrates the effect of prioritizing multiple uses of land resources for food, feed or bioenergy, while maintaining a low nitrogen load to the environment. In conclusion, even after drastic landuse changes the bioenergy supply as final energy will not exceed 184 PJ annually (including 26 PJ processed biowaste sources) by far lower than the annual domestic total energy consumption ranging between 800 and 850 PJ yr^{-1}.

1. Introduction

Bioenergy for heat, power and transport are foreseen to be part of future energy supply [1]. Energy security for the transport sector, the substitution of fossil energy sources and reduction of green house gas (GHG) emissions are specific targets. Given the assumption that biomass resources are limited, optimization of the biomass production from land resources is desirable. The biological production potential of cultivated land is a combination of physiographic conditions (soil quality and climate), crop type, seed material, cultivation method, fertilizer and irrigation. Assessment of the potential sustained biomass supply is needed in order to evaluate the possibility of switching from fossil-based carbon to actual biomass sources for energy and goods. Furthermore, goals for the transport sector within EU set to 10% biofuels by 2020 have raised the question of increasing the biomass-based liquid fuel production.

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doi:10.1016/j.biombioe.2010.04.020

For Denmark, energy policy goals have been set by the Danish government [2]. By 2011, the Danish energy supply from renewable energy sources should be 20%. The utilization of biomass is closely linked with the structure of the Danish bioenergy sector. The combustion of biomass for district heating as well as combined heat and power production (CHP) are well developed sectors, in the absence of a domestic wood pulp and paper industry that would compete for the same wood resources. By 2005, a fuel ethanol industry was non-existing.

The present potential for bioenergy may be assessed from various production statistics. However, there is great uncertainty, e.g. due to risk of double counting or missing registration of biomass consumption. The classification of feedstocks is also confusing (e.g. is straw agricultural waste or a primary fuel?). The energy content per unit of the original input feedstock will gradually decrease as the carbohydrates are consumed ("burnt") during consecutive recycling steps. Therefore, the primary production of biomass is the upper limit of what can potentially be supplied as bioenergy, provided the biomass can be made available through harvest and transport.

In 2005, the share of renewable energy in Denmark was 15.5% of domestic total energy consumption. So far, 70% of all renewable energy production (117 PJ in 2005) has been based on biomass, mostly wood and renewable waste (excluding household waste) for district heating and combined heat and power [3]. About half of the wood fuel consumption is currently used by household wood stoves and this wood fuel will remain unavailable for the industry unless household wood stoves are changed to other heating systems.

Estimation of biomass feedstock potentials in future scenarios may be based on various modeling approaches. Often the modeling is based on large, complex models with little transparency and rests on assumptions of higher plant production in a changing climate, higher residue utilization rates, and a certain land area available for dedicated energy crops in different scenario assumptions on oil price and environmental concerns such as biodiversity and water quality in the agricultural landscape [4]. Since biomass is all kinds of photosynthetic tissue, potential bioenergy crops may for simplicity be grouped into starch, oil, sugar, grassy and woody biomass products like in two recent projects under Intelligent Energy Europe, REFUEL [5,6] and RES2020 [7]. REFUEL includes an assessment of biomass potentials for biofuel feedstock production in Europe, which is based on IIASAs agro-ecological zones modeling framework. It has been updated and expanded for biofuel productivity assessments. RES2020, "Monitoring and Evaluation of the RES directives [8] implementation in EU27 and policy recommendations for 2020" aims at examining the implications of the achievement of these targets to the European Economy using a technology-rich energy model in a tradition that dates back to the first oil shock in the 1970s. The use of biomass potentials for energy is one of the technologies considered in RES2020. The possible competition between crops for food&feed versus bioenergy is obvious, and the relevance of the question at the global scale is stressed by different authors. Johannson et al. [9] argue that globally, the agricultural sector is not able to supply bioenergy from primary biomass to any great extent, but that agricultural waste is a valuable source of bioenergy feedstock. Imhoff [10] estimated that current human appropriation of net primary production (NPP) is 15–25% by comparing NPP satellite data and food, feed and forest product statistics. Apparently, there is no consensus on the magnitude of future bioenergy potentials and of the role of the agriculture and forestry sectors in this question.

The aim of the present work is to provide a simple transparent analysis of bioenergy yields from crops that are suitable for bioenergy in Denmark. The use of material and monetary inputs for each crop, constraints in resource availability such as area of cultivated land, and crop rotation requirements are considered. Tools within operations research, e.g. linear programming can be used to find analytically optimal solutions to production costs under multiple constraints.

The basic idea in this study is to use linear programming for providing a resource focused (primary biomass) and demand driven [11] (energy) cost minimization model that can estimate the biomass supply in Denmark. The model explores links between energy demand, bioenergy and food&feed supply via the price of fossil oil. This simple approach serves the purpose of creating overview of primary bioenergy potentials, food&feed production and consequences for landuse. Constraints to biomass production are often included in bioenergy potential modeling e.g. by excluding biomass extraction from protected nature types [4]. Here, effects of changed crop area distribution on Danish environment will include examples of important nitrogen loads to water and atmosphere. The outcome of the model is a crop area distribution of Danish cultivated land and an assessment of the biomass feedstock available for conversion to heat, electric power and transport fuels. The emphasis is on the biomass production phase. The industrial conversion phase is characterized by standard biomass to bioenergy conversion efficiencies. Scenarios are set up that will demonstrate consequences of constraints due to food&feed supply, environmental and legal bindings on landuse and crop use.

2. Methods

2.1. *Energy input and output of related crops*

An analytical approach for addressing and analyzing such complex agendas may be quantitative numerical modeling putting focus on cost minimization under different sets of constraints given by resource limitations and the environment.

In this application we study the Danish area distribution of arable, forest, set-aside and fallow land resulting from minimization of the total production costs of crops. The additional fossil fuel energy necessary to meet a given reference demand for energy services as a fuel mix is analysed in scenarios. A central scenario assumption is the price of fossil energy, which will compete with bioenergy. The key results of the analysis will be identification of the scenario parameters that are most important for the future supply of biomass for energy.