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# Bioenergy futures in Sweden – Modeling integration scenarios for biofuel production

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ABSTRACT

Use of bioenergy can contribute to greenhouse gas emission reductions and increased energy security. However, even though biomass is a renewable resource, the potential is limited, and efficient use of available biomass resources will become increasingly important. This paper aims to explore system interactions related to future bioenergy utilization and cost-efficient bioenergy technology choices under stringent $CO_2$ constraints. In particular, the study investigates system effects linked to integration of advanced biofuel production with district heating and industry under different developments in the electricity sector and biomass supply system. The study is based on analysis with the MARKAL_Sweden model, which is a bottom-up, cost-optimization model covering the Swedish energy system. A time horizon to 2050 is applied. The results suggest that system integration of biofuel production has noteworthy effects on the overall system level, improves system cost-efficiency and influences parameters such as biomass price, marginal $CO_2$ emission reduction costs and cost-efficient biofuel choices in the transport sector. In the long run and under stringent $CO_2$ constraints, system integration of biofuel production has, however, low impact on total bioenergy use, which is largely decided by supply-related constraints, and on total transport biofuel use, which to large extent is driven by demand.



## 1. Introduction

An increased share of renewable energy in the energy system is critical to mitigate climate change as well as to handle other energy-related environmental challenges. For many countries and regions, renewable energy is also a way to improve energy security of supply through a more diversified energy mix and less reliance on imported energy carriers. Bioenergy is currently the largest source of renewable energy [21], and a further future increase in bioenergy demand is likely with increasingly ambitious climate and energy security targets. But even though biomass is a renewable resource, the annual potential is limited due to land scarcity. Efficient use of available biomass resources will thus be increasingly important.

Several potential future technologies, currently at the stage of research and development or early commercialization, have the ability to significantly increase the value and efficiency of bioenergy utilization. Advanced biorefineries based on conversion of lignocellulosic biomass to high value energy carriers such as transport fuels could be one key option. In contrast to *first-generation biofuels*, which primarily are based on traditional food crops, *second-generation biofuels* can be based on by-products from forestry and high yield energy crop alternatives, such as energy forest. Since second-generation biofuel production processes often have a relatively large net surplus of heat, integration with heat demands in district heating systems and/or existing industry can further increase the system efficiency and lower the costs (see e.g. Refs. [1,25]).

New advanced biorefinery technologies are linked to substantial development and capital costs. Further, integration of newly developed technologies in, e.g., industrial applications could imply risks for commercial activities. As a consequence, few actors are willing to take on necessary investments unless policies are in place ensuring long-term societal commitment for environmental targets and related initiatives. In turn, policymakers are in need of decision

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support for creation of long-term strategies leading in a beneficial direction for society. In addition to detailed technology assessments (e.g., on plant level), system analyses of potential technology options and identification of future cost-efficient technology pathways are therefore essential to enable future environmental and societal challenges to be met. While such studies involve broad approaches and aggregated views of the system, the risk of over-simplification of the representation of the underlying technological solutions must be carefully considered.

While it has been shown that the stringency of carbon targets is a significant determinant for future bioenergy utilization (e.g., Ref. [8]), the cost-effectiveness of different types of bioenergy utilization is likely to also depend on several other factors in the surrounding system. Factors of importance can be both of a direct and indirect character. For instance, changes in biomass supply and development of new bioenergy technologies may have a direct effect on the future bioenergy utilization, but also the development of competing non-bioenergy based technologies can have significant impacts. Through effects on biomass markets, seemingly unlinked developments in other parts of the energy system can give rise to system impacts over sector boundaries. The system dynamics are complex, and different factors can amplify as well as offset each other depending on the specific system situation and direction of change.

This paper aims to explore system interactions related to future bioenergy utilization and robust cost-efficient bioenergy technology strategies for the case of Sweden. Specifically, the study investigates possibilities for increased bioenergy conversion efficiencies through integration of advanced biofuel[1] production with district heating or industrial systems, and system effects of different developments in the electricity sector and biomass supply system. The main questions of investigation are:

- Under stringent $CO_2$ constraints, how can integration of second-generation biofuel production with existing industry or district heating systems influence future cost-efficient biomass utilization?
- To what degree is the biomass supply potential a critical determinant for cost-efficient biomass utilization in the medium to long term?
- How do large transitions in the electricity sector linked to non-biomass low-carbon electricity supply (e.g., nuclear power) and demand for electricity (e.g., through electricity export) impact cost-efficient biomass utilization?

The study is based on an energy system modeling approach applying a comprehensive view of the Swedish energy system and a long-term time horizon to 2050. It builds upon earlier work focused on the bioenergy system effects of $CO_2$ and fossil fuel reduction [8].

Broad, bottom-up energy system modeling studies, e.g., on national or global level, such as Refs. [7,8,16,28,35]; often have a comparably large selection of different types of energy technologies represented. However, while there are exceptions, focus is often put on stand-alone plants rather than integrated solutions with possibilities of higher system efficiencies. Further, much attention is often given to a relatively low number of future scenarios, which under certain conditions may be optimal from a cost perspective, but from other aspects (e.g., social, political, industry strategy-wise) might be unlikely. As previously highlighted (see e.g., Refs. [36,37,5,6]), it is of importance to utilize models not only to establish single optimal solutions but through parameter variations and broader set of assumptions analyze lessons to be learned of the dynamics of the studied systems and of alternative, "near-optimal" system developments.

In contrast to system studies at higher geographical scale, studies at a lower system level (plant level, etc.) could to a higher degree go into technological details regarding advanced biorefineries and integration opportunities with other energy conversion systems, e.g., in industries, examples include Refs. [1,10,12,22]. However, such studies tend to have a strong dependence of exogenous scenario assumptions regarding, e.g., energy prices and marginal effects and they lack ability to capture system effects and interactions linked to biomass use at a higher system level.

This study seeks to bridge the gap between, on the one hand, high system level studies with lack of technological detail in regard to future options for advanced biomass use and, on the other hand, lower system level studies with simplified treatment of the dynamics of the surrounding system development.

## 2. Method and data

In the following sections, the model-based analysis approach and relevant input data are presented. Section 2.1 provides a brief description of the model; Section 2.2 presents the analysis approach applied as well as definition of model cases and scenario assumptions; Sections 2.3 presents technology data assumptions of special relevance for the study.

### 2.1. Model

The study is based on analysis with the MARKAL_Sweden energy system model. MARKAL_Sweden is an application of the well-established MARKAL model [26] and can be described as a dynamic, bottom-up, partial equilibrium energy system model. Through optimization, the model provides the overall welfare-maximizing system solution that meets the defined model constraints over the studied time horizon. Welfare-maximization implies that the cost of energy service supply and costs due to losses in consumer surplus are minimized. An important aspect is the models ability to invest in new technology capacity among the defined current and future technology options, if this lowers the overall system cost. Among other aspects, model constraints include energy service demands, emission restrictions and capacity constraints in supply and conversion technologies. Different versions of the MARKAL_Sweden model have been used in several earlier studies. The most recent, which the current study builds upon and from which additional model descriptions (and results) can be obtained, are Refs. [7,8].

MARKAL_Sweden applies a long-term time horizon reaching from 1995 to 2050.[2] The time horizon is divided in 5-year model periods, each represented by a model year (1995, 2000, …, 2050). Time resolution per model year differs between energy carriers: electricity is represented by three seasonal and two diurnal periods, heat is represented by three seasonal periods, and other energy carriers are represented on an annual basis. The model applies perfect foresight (no uncertainty of future developments) and, in the current study, a discount rate of 6% is applied.[3]

[1] The term *biofuel* is here used to denote biomass-based transport fuels (liquid or gaseous).

[2] Model costs are given in the monetary value of 2010. An exchange rate between Swedish Krona (SEK) and Euro (EUR) of 9 SEK/EUR is used.

[3] The discount rate has in the model no effect on the rate of $CO_2$ reductions in the system as this is handled through emission constraints for each respective model year (see Section 2.2). The chosen discount rate level is within the range commonly used in energy system modeling, although in the upper part of this range in order not to exaggerate the willingness to invest in capital intensive technologies.