YSSP Report
Young Scientists Summer Program

GHG Efficient Policies for Biofuel Production on Agricultural and Abandoned Agricultural Land

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Abstract

Biofuels as a substitution for fossil fuels constitutes one possible greenhouse gas mitigation option. However, there are limitations of and competition over the biomass that could be used. In addition, there are other possible mitigation options that might be more cost efficient to use. For this report, an economic spatial localization model was used to investigate the organization of biofuel production from agricultural land. In particular, the potential of using abandoned agricultural land and the usefulness of using the biofuel as a mitigation option was studied. The results show cost savings with using abandoned agricultural land, while using this type of land can be larger due to land use change emissions. Under a climate target, biofuel from abandoned land can be preferable to other options due to their low costs, despite the potential high emissions.
Further research could include implementation of more technologies and a widening to include a larger regional unit and trade effects.

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Nomenclature

Sets

$\tilde{G}$	Set of feedstock production regions
$\tilde{I}$	Set of biofuel production regions
$\tilde{H}$	Set of end-use regions
$\tilde{S}$	Set of fuel change cost categories
$\tilde{F}$	Set of feedstock cost categories
$\tilde{V}$	Set of facility types
$\tilde{K}$	Set of fuels
$\tilde{K}'$	Subset of biofuels
$\tilde{K}''$	Subset of fossil fuels
$\tilde{K}'''$	Subset of blended fuels
$\tilde{A}$	Set of abandoned land cost categories
$\tilde{M}$	Set of land classes

Variables

$I_{v,i}$	Binary investment variable	1/0
y_i	Biofuel production	m^3
$y_{i,g}^{TR}$	Biofuel flow between regions	m^3
$x_{f,i,g}^{TR}$	Feedstock flow between regions	Tonne
$x_{f,g}$	Feedstock	Tonne
$x_{a,g}$	Feedstock from abandoned land	Tonne
$y_{k,h}$	Fuel use	m^3
$\hat{y}_{k,h}$	Fuel use, measured in energy	TJ
$\hat{y}_{s,k,h}$	Fuel use per cost category, in energy	TJ
Y	Total biofuel production	Tonne
$c_{i,v}^{INV}$	Investment cost	EURO
c_i^{OP}	Production costs	EURO
c_i^{FEED}	Feedstock cost	EURO
$c_{i,g}^{TR}$	Feedstock transport cost	EURO
$c_{i,h}^{DISTR}$	Biofuel distribution cost	EURO
c_h^{FUEL}	Cost for fuel use change	EURO
$c_g^{L\_CONV}$	Cost for feedstock from abandoned land	EURO
$e_{i,g}^{FEED}$	Emissions from feedstock	Tonne CO_2
e_i^{OP}	Emissions from biofuel production	Tonne CO_2
$e_{i,g}^{TR}$	Emissions from feedstock transport	Tonne CO_2
$e_{i,h}^{DISTR}$	Emissions from biofuel distribution	Tonne CO_2
e_g^{LUC}	Emissions from land use change	Tonne CO_2
e_h^{die}	Emissions from diesel	Tonne CO_2
e_h^{gas}	Emissions from gasoline	Tonne CO_2
e^{TOT}	Total emissions	Tonne CO_2

$D^{k,h}$	Biofuel demand function

Parameters

$\bar{x}_{f,g}$	Available feedstock	Tonne
$\bar{x}_{a,g}$	Available feedstock, abandoned land	Tonne

$y_{k,h}^{0}$	Initial level of feedstock	m^3
$\hat{y}_{k,h}^{0}$	Initial level of feedstock, in energy	TJ
p_{k}^{0}	Initial fuel price	EURO/m^3
$\overline{\gamma_k}$	Maximum share biofuel in blended fuel	
$\Delta\vartheta_{a,g,m}$	Difference in carbon stock	Tonne CO_2
$d_{g,i}$	Distance between regions	km
τ_k	Fuel –energy conversion coefficient	TJ/m^3
$c_{s,k,h}^{CONS}$	Costs for changing fuel use	EURO/m^3
$p_{f,g}$	Feedstock cost	EURO/tonne
θ_a	Conversion cost	EURO/tonne
ω_g	Production cost, abandoned	EURO/tonne
ε_{die}	Emission intensity for diesel	Tonne CO_2/m^3
ε_{die}	Emission intensity for gasoline	Tonne CO_2/m^3
Y^{*}	Biofuel production target	Tonne
R^{*}	Emission reduction target	Tonne CO_2

Introduction

Greenhouse gas emissions from the transport sector constitutes a large share of total emissions in the world (IEA, 2020). Among GHG mitigation options, biofuel has proved one relatively easy to implement in the energy and transport sector, but with sustainability problems such as competition with food production and forestry, impact on biodiversity and the trade-off with forest conservation (Jeswani et al., 2020). How, and how much should be produced and where it should be used is not known. The most sustainable feedstock option is using residues from agriculture, food and forestry, but for large scale implementation, more feedstock would be needed (Börjesson et al., 2013). The possibilities of using large amounts of biofuel need to be addressed.

Competition with food production globally occurs in particular when first generation feedstock is used, that is food crops such as rapeseed and cereals (Jeswani et al., 2020). One alternative is to grow second generation energy crops on grassland and land for forage production. By using this land there is no direct competition with food production, but as fodder is an input for animal production, food production is affected. Another discussed source of land for biofuel production is abandoned agricultural land. This land is generally low productive, but it might provide a good basis to grow energy crops on (Campbell et al., 2008, Börjesson et al., 2013). The data on abandoned land is scarce, and whether or not abandoned land should be used for biofuel production is uncertain.

GHG emissions arises also from biofuels, in most cases (Börjesson et al, 2010), but much less than fossil based fuels. In addition, land use change (LUC) emissions appears if land is converted from one land class to another to grow bioenergy crops on it (Berndes et al., 2011). This is important when using abandoned agricultural land, as, depending on how much the land have changed, conversion of land could both give positive and negative emissions from changes in the carbon stock.
For biofuels, the implementation of production requires investment in large production facilities, and logistics for transporting biomass and biofuel. Many studies have been done on the localization of facilities, and impact on cost and emissions, among other things. Some focus on agriculture, others on forestry, typically where one type of land is more abundant (Zandi Atashbar et al., 2018). There is a trade off between large transport costs and economies of scale of facilities which opts for centralized production with few facilities. Further, for biofuels the spatial heterogeneity of feedstock costs, availability and fuel demand have impact on how production should be organized. Transport costs have been found important for the localization (e.g. Wetterlund et al., 2013) and also the feedstock distribution (e.g. Natarajan et al., 2014).

From an economic perspective, biofuels are preferred to reduce GHG emissions if they are a cost-effective mitigation option. For most abatement options, the marginal cost of abatement increases. The increase in marginal costs is evident in the case of biofuels, where the land used for biomass production is finite, and used for other purposes, so increased outtake would increase competition and thus costs. With the model used in this report, Nordin et al. (2021) found a cost in Sweden of 0.26 Euro per kg CO_2 (for ethanol covering 21% of domestic gasoline use), while e.g. Millinger et al. (2018) found the marginal cost for lignocellulosic ethanol to be EUR 0.55 per kg CO_2 in 2020 in Germany. As a comparison, the EU ETS carbon price was around EUR 0.024 per kg CO_2 during 2019 (European Commission, 2020). However, the High-Level Commission on Carbon Prices (2017) concludes that the carbon price needed to reach the Paris Agreements temperature target is at least EUR 0.043–0.085 per kg CO_2 by 2030. Targeting of emissions directly are theoretically the most efficient way to decrease GHG emissions (see e.g. Baumol et al., 1988). This can however be more difficult to implement, or to accept for people (Brännlund and Persson, 2012).

Focusing on biofuels, examples are Hedeneus and Azar (2009) who minimize costs for emission reduction focusing on the options of growing feedstock for bioenergy, or saving trees for carbon sequestration, in a dynamic model. Those options compete over land with each other and employing one would therefore decrease the possible use of the other. They find that it in general is better with bioenergy. On the contrary, Vass and Elofsson (2016) find, also using a dynamic model over the forest sector, that afforestation in general is more cost efficient, in particular at higher emission reduction targets.

When deciding on producing biofuel, it is important to know if it is an efficient mitigation option and also that the land is used efficiently. Abandoned land is a potential low-cost source of land. Therefore, it is important to investigate if this land would be used in biofuel production, and implications for GHG and land use. The following research questions are the base for this report, to be answered and analyzed by modelling ethanol production on agricultural land in Sweden:

- How does use of abandoned agricultural land affect organization of biofuel production?
- How does ethanol production differ when a greenhouse gas emissions reduction target is used rather than a production target?
- How are emission reduction targets met when biofuel production is an explicit abatement option?
- How do assumptions on land use change emissions from abandoned land impact meeting the emission reduction targets?

The contribution of this study is the focus abandoned land for biofuel production, important to assess if it rises the potential for biofuel. The other contribution is a comparison of the production target, which is often studied, to a GHG target. With spatially explicit data the role of regional differences for the GHG target can be analyzed.

The report begins with a description of the model, continues with a description of the case study area and data, explains the analyzed scenarios and explains the results. Lastly a discussion of the results and their policy implications are analyzed.

Model

To answer the posed questions an economic localization model is used. The model captures the trade-off between agglomeration forces from benefits of using economies of scale and centralizing to large production facilities, and dispersion forces due to transport costs and spread-out feedstock availability. The model optimizes the localization of biofuel production facilities, biofuel feedstock uptake, biofuel distribution and fuel use, by minimizing supply chain costs, given a policy target in the form of a production target or a GHG emission reduction target. The base of the model is described in Nordin et al. (2021). Therefore, only a brief overview is given here, along with essential variables and parameters. The new developments are the following:

- endogenous fuel demand
- abandoned land use
- land use change emissions

Localization model

The model described in Nordin et al. (2021) is followed, except that the demand for biofuel is modelled differently. Variables decided in the model are feedstock production, feedstock flows to production facilities, investment decisions, biofuel production, biofuel flows from facilities to end users, end use of biofuel and GHG emissions. Here, regions in the model are indexed *g* belonging to the set $\tilde{G} = 1, 2, \dots G$ for feedstock production, *i* belonging to $\tilde{I} = 1, 2, \dots G$ for biofuel production and *h* belonging to $\tilde{H} = 1, 2, \dots, G$ for end-use regions. *f*, belonging to $\tilde{F} = 1,2, \dots, F$, denotes feedstock cost categories, *v* belonging to $\tilde{V} = \{high, low\}$, the type of facility (high or low capacity). The model is constrained by available feedstock levels, costs for feedstock, transport, production, investment and distribution and facility capacities.

The investment in a facility, $I_{v,i}$ can be in high or low capacity (*v*) facilities, with associated investment costs $c_{i,v}^{INV}$. The cost depend on the capacity level of the facility and has economics of scale. There are upper and lower bounds on the capacities, where low capacity facilities are smaller than high capacity facilities. Production of biofuel y_i from feedstock, and production costs c_i^{OP}in each region depend linearly on the feedstock input. The feedstock input at one facility equals the sum of feedstock flows to that region,$\sum_i x_{f,i,g}^{TR}$, from different supply regions *g*. In each supply region there is a maximum available level of feedstock, $\bar{x}_{f,g}$ for each feedstock category. The cost of feedstock is based on the opportunity cost of production and increases with the amount of land used due to competition over land. Division of the available land into categories *f* is used to model the costs with an increasing piecewise linear cost function $c_i^{FEED} = \sum_g \sum_f p_{f,g} x_{f,i,g}^{TR}$. Feedstock of the lowest cost level would be chosen until its maximum capacity, limited by the available land for the category, is exhausted, before the next category is used.

The transport of each feedstock flow $x_{f,i,g}^{TR}$ has a linear cost $c_{i,g}^{TR}\left(x_{f,i,g}^{TR}, d_{g,i}\right)$ depending on the feedstock volume and the distance $d_{g,i}$ between the regions. Distribution of biofuel, $y_{i,h}^{TR}$, to different end use regions *h* has linear costs $c_{i,h}^{DISTR}\left(y_{i,g}^{TR}, d_{h,i}\right)$ depending on the biofuel volume and the distance, in the same way as feedstock transport. Both the relation between feedstock supply and use, and biofuel production and demand, must hold with equality.

Emissions $e_{i,g}^{FEED}$, e_i^{OP}, $e_{i,g}^{TR}$, $e_{i,h}^{DISTR}$ from feedstock production, biofuel production, feedstock transport, and biofuel distribution are modelled linear with their associated processes.

Fuel demand

The approach to model demand is similar to Vass and Elofsson (2016) who has change in fuel use as an alternative abatement option. Consumers are assumed to be able to use different types of fuels for transport (gasoline and diesel). Here, the ethanol will come in as a possible fuel, with its cost and emissions. The fossil fuel types are not fully substitutable with each other, so switching would come at a cost. A fuel with blended biofuel is perceived as qualitatively equal to the fossil fuel (i.e. indifferent between gasoline and ethanol-gasoline blend).

The baseline level of fossil fuel is $y_{k,h}^0$, where *k* belongs to $\tilde{K} = \{eth, gas, die, Egas\}$ (with *eth* for ethanol, *gas* for gasoline, *die* for diesel and *Egas* for ethanol-gasoline blend fuel), and the subset biofuels $\widetilde{K'} = \{eth\}$, and subset of fossil fuels $\widetilde{K''} = gas, die\}$. For biofuels this is assumed to be zero.

$$y_{k,h}^0 = 0 \; \forall k \in \widetilde{K'} \; and \; h \in \tilde{H} \qquad (1)$$

Levels of biofuel and fossil fuel can change to substitute between fossils and biofuels, and to change transport of a specific fuel (or fossil-biofuel blend). Changes in fuel are denoted by $y_{k,h}$. For biofuels they are positive as they start from zero, and equals the total produced biofuel:

$$y_{k,h} = \sum_i y_{i,h}^{TR} \; \forall k \in \widetilde{K'} \; and \; h \in \tilde{H} \qquad (2)$$

$$y_{\,k,h} \geq 0 \; \forall k \in \widetilde{K'} \; and \; h \in \tilde{H} \qquad (3)$$

To be able to compare the fuels for use for transport, their values are converted into energy equivalents by the transformation coefficients τ_k to TJ (equation 4). These are represented by blended fuels, where ethanol blends with gasoline (eth, gas) to *Egas*, and diesel does not blend, but keep notation *die,* with $\widetilde{K'''} = \{Egas, die\}$. The quantities are represented by $\hat{y}_{k,h}$. This implies an energy-amount of gasoline is possible to be substituted with an equivalent energy amount of ethanol, while the blended fuel energy amount does not change (i.e., no change in fuel quality for consumers).

$$\hat{y}_{Egas,h} = \tau_{gas} y_{gas,h} + \tau_{eth} y_{eth,h} \forall h \in \widetilde{H} \qquad (4)$$

$$\hat{y}_{die,h} = \tau_{die} y_{die,h} \ \forall k \in h \in \widetilde{H} \qquad (5)$$

The share of biofuel in the fossil/biofuel blend has to be below the cap $\overline{\gamma_k}$, for *Egas*:

$$\tau_{eth} y_{eth,h} \leq \overline{\gamma_{egas}} \left(\hat{y}^0_{k,h} + \hat{y}_{egas,h} \right) \qquad (6)$$

This means substitution of gasoline for ethanol is only possible to a limited extent. With a climate target, total fuel use can change to decrease emissions. However, if transport fuel use decrease, this comes at a cost of changed consumer surplus, when moving from the optimal consumption level. The equation below shows the costs (calculations in the Appendix A1), but biofuel production costs are excluded as they are stated explicitly in Nordin et al. (2021).

$$c_h^{FUEL} = -\sum_{k \in \widetilde{K'''}} \left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h} + \hat{y}_{k,h}} \left(D^{k,h} \left(\hat{y}_{k,h} \ \right) - p^0_k \right) d\hat{y}_{k,h} \ \right) - \sum_{k \in \widetilde{K'}} \left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h} + \hat{y}_{k,h}} p^0_k d\hat{y}_{k,h} \right) \ \forall \ h \in \widetilde{H} \quad (7)$$

Where p^0_k are initial prices and $D^{k,h}$ are the demand functions for blended fuels. The intuition is that with a lower consumption level, there are lower fossil fuel costs, but an even larger decrease in consumer surplus. In addition, the biofuel that substitutes fossil fuel leads to decreased fossil fuel purchase costs. However, ethanol production costs occur instead.

The utility functions are assumed quadratic, thus the demand functions linear. Integrals are therefore quadratic and non-linear. To avoid non-linear equations, which make integer programming problems difficult to solve, the integrals are approximated with piecewise linear equations. Thus, for each fuel, the total possible fuel change is now divided in *s* belonging to $\tilde{S}$ *= 1,2,…,S* segments,

$$\hat{y}_{k,h} = \sum_s \hat{y}_{s,k,h} \ \forall k \in \widetilde{K'''} \ and \ h \ \in \widetilde{H} \qquad (8)$$

The demand function is assumed constant for each cost segment

$$D^{k,h} = p\left(\hat{y}_{s,k,h} \right) = \ c^{CONS}_{s,k,h} \ \forall k \in \widetilde{K'''} \ , h \ \in \widetilde{H} \ and \ s \ \in \tilde{S} \qquad (9)$$

$$c^{CONS}_{s,k,h} < c^{CONS}_{t,k,h}, \ \forall k \in \widetilde{K'''}, h \ \in \widetilde{H} \ and \ s < t \qquad (10)$$

In this way the integrals become linear. This allows for two ways of reducing emissions; by substituting fossils for biofuels with lower emissions, or by only reducing fossils. Each way entails different costs.

Land use model abandoned agricultural land

In Nordin et al. (2021) only current agricultural land was allowed to be used. Here the model is extended by also allowing use of abandoned land. This land has properties to be good enough to use for agriculture, and would in general be easier to convert back to agricultural land than forest. However, as it is abandoned it has in general lower yields, and besides the running costs, there is also a conversion cost to convert it back to agricultural use. The main purpose with the land use model is to be able to analyse the effect on land use change emissions. It is also possible to analyse how much abandoned land is profitable to take into use, and what the effect would be of forcing a use of abandoned land.

The modelling is similar as for other feedstock, with a piecewise linear cost function. There is a maximum available feedstock per region, divided into equally sized segments $\bar{x}_{a,g}$, *a* belong to $\tilde{A}$=1,...,A segments. The feedstock cost of abandoned land into cultivatable land, $c_g^{L\_CONV}$, has increasing marginal costs with the conversion cost increasing with *a*, so that the first segment is cheaper than the second to convert, each segment with cost θ_a. There is also a cost for production,ω_g.

$$c_{a,g}^{L\_CONV} = \theta_a x_{a,g} + \omega_g x_{a,g} \; \forall a \in \tilde{A} \; and \; g \in \tilde{G} \qquad (11)$$

The equation gives the cost for a segment of feedstock, and as they are different, $x_{1,i,g}^{TR}$ would be exhausted before $x_{2,i,g}^{TR}$ is used, thus constituting the increasing function.

Land use change emissions

Land use change emissions are introduced for the use of abandoned agricultural land, as this land use is assumed to include conversion of land. The emissions per feedstock unit are based on the difference in carbon stock between abandoned agricultural land and bioenergy feedstock plantation, $\Delta\vartheta_{a,g,m}$ in CO_2 for each cost category. The index *m,* belonging to $\widetilde{M}$*= 1,2,…,M* is the assumption on initial land class for abandoned land. *m* is used to model different types of assumptions on what the abandoned land is classified as. Emissions e_g^{LUC} are calculated:

$$e_g^{LUC} = \sum_a x_{a,g} \cdot \Delta\vartheta_{a,g,m}, \forall a \in \tilde{A}, m \in \widetilde{M} \; and \; g \in \tilde{G} \qquad (12)$$

Emissions from fossil fuels

For fossil fuels, change in emissions e_h^{die}, e_h^{gas} are calculated based on the changes volume for each fuel. That is, initial levels are not included. ε^{gas}, ε^{die} are emission coefficients of the respective fuels.

$$e_h^{die} = y_{die,h}\varepsilon_{die} \; , \forall g \in \tilde{G} \qquad (13)$$

$$e_h^{gas} = y_{gas,h} \; \varepsilon_{gas} \; , \forall g \in \tilde{G} \qquad (14)$$

Total emissions in emissions $e^{TOT}$are in general negative as they include reductions in fossil emissions, and are given by:

$$e^{TOT} = \sum_h \left(e_h^{die} + e_h^{gas}\right) + \sum_g \sum_i \left(e_{i,g}^{TR} + e_{i,g}^{FEED}\right) + \sum_g e_g^{LUC} + \sum_h \sum_i e_{i,h}^{DISTR} + \sum_i \qquad (15)$$

Policy targets

Two types of policy targets are modelled, production and climate targets.
A production target is set on national level, defined as an annual production target Y^*:

$$Y \geq Y^* \qquad (16)$$

An annual climate emissions reduction target R^* is set on a national level:

$$-e^{TOT} \leq R^* \qquad (17)$$

Objective of the model

Biofuel production and fuel use are optimized by minimizing the costs for biofuel production and fuel use change, given one or two of the policy targets. The problem can be described as follows:

$$\underset{x_{f,g}, x_{f,i,g}^{TR}, I_{v,i}, y_{i,}, y_{i,h}^{TR}, y_{gas,h}, y_{die,h}}{\text{Argmin}} \quad \sum_h c_h^{FUEL} + \sum_i \sum_v \left(c_{i,v}^{INV} + c_i^{OP} + c_i^{FEED}\right) + \sum_i c_i^{TR} + \sum_i c_i^{DISTR}$$

$s.t.$

Eq. (1) - (17), and eq. (1) - (7) and (9) - (13) in Nordin et al (2021),

$x_{f,g}, x_{f,i,g}^{TR}, y_{i,}, y_{i,h}^{TR} \geq 0$ and $I_{v,i} \in \{0,1\}$

$\forall f, h \in \widetilde{H}, i \in \widetilde{I}, g \in \tilde{G} \; and \; v \in \tilde{V}$

The model is simulated numerically with relevant data. For this the optimization software GAMS is used, with the OSICPLEX mixed integer linear programming solver, using GAMS version 30.3, with the model solved at 0.5% gap tolerance from optimality.

Case study region Sweden and data

On Sweden

Sweden is a country dominated by forest (about two thirds), while there are some productive soils, and agricultural land mostly in the in the southern and southeastern parts of the country (7% of the land area). There is a relatively large share agricultural land used for grass production for silage (ley), to feed animals (Statistics Sweden, 2019). The agricultural land has decreased over the years, so the area abandoned agricultural land has increased (Statistics Sweden, 2019) and some agricultural land has turned into forest (Olofsson and Börjesson, 2016).

The Swedish population is distributed similarly as agricultural land; the largest density in the south and eastern parts (Statistics Sweden, 2020a). Of transport fuels, 23% were biofuels in 2018, but the largest share of feedstock was imported (Swedish Energy Agency, 2019c). Sweden follows the renewable energy directive by the EU, which stipulates that 14 % of transport fuel consumption should be renewable in 2030 (European Parliament, 2018). With 23% in the year 2018 (Swedish Energy Agency, 2019c), the target is accomplished. The more ambitious target to reduce greenhouse gas emissions in the transport sector by 70% until 2030, (Government Offices of Sweden, 2017) is not yet reached. Sweden also has mandatory reduction of fossil emissions from fuels, by e.g. blending of biofuel for fossil fuel suppliers. As a proposal for 2030, the Government proposes at least 28% reduction for gasoline and 66% for diesel, and the share should increase over time (Swedish Energy Agency 2019a).

The focus is on ethanol production from lignocellulosic material (reeds canary grass). The choice is made as if the technology is readily developed, the quantitative potential is large as it uses non-food biomass (Börjesson et al., 2013), and the relative easiness to use in the current vehicle fleet, possible to blend with gasoline.

Data summary

The data used for the model is described in Nordin et al (2021), here brief overview of that data is provided, and detailed description over additional data.

The regional unit are the municipalities in Sweden, and distances are measured between centers of all regions. 50% of all current land for ley production is assumed to be allowed to be used for biofuel feedstock production, and in addition 10% of cropland. The feedstock used is reed canary grass, which suits Swedish conditions. With a regionally differentiated yield data, this result in that the area can produce maximum 5.8 million tonnes feedstock, with the regional distribution showed in Figure 1. This is used to produce ethanol, with a technology that converts feedstock to ethanol, 0.3 m^3 ethanol per tonne feedstock.

Costs for feedstock are regional and based on production costs for silage and alternative costs for spring barley production (see Figure 1). The increasing costs, in the piecewise linear equation, are estimated using own-price elasticities for forage. The costs categories are divided with 25% ley land in category one, the second 25% in cost category 2 and the 10% of cropland in category 3.
The costs for production of ethanol and annualized investment cost are equal for all regions, and the capacities considered per year are 15-180,000 m^3 ethanol for low capacity facilities and 180-360,000

m^3 ethanol for high capacity facilities. Transport costs for feedstock and biofuel distribution are assumed to be by truck and are based and distance and quantities.

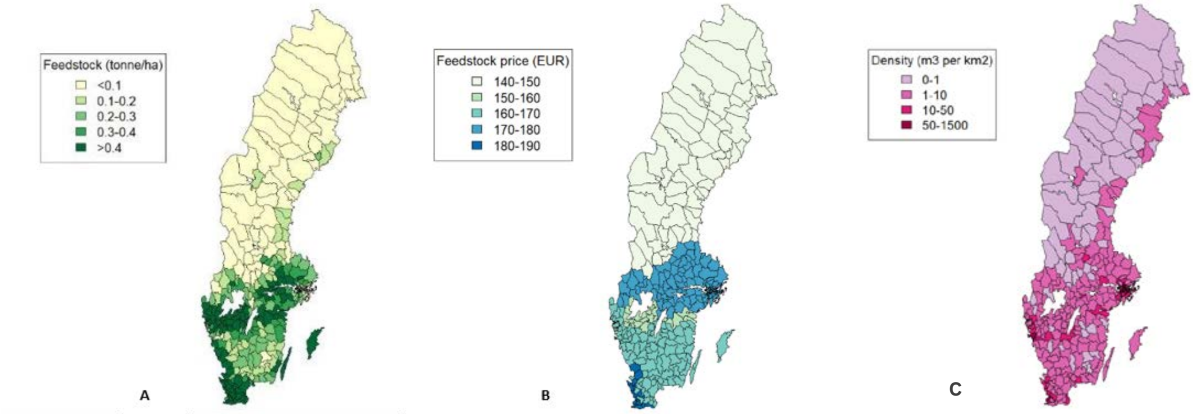

Figure 1 Background data. Feedstock density (A), feedstock cost (B) and fuel use density (C). Source: Nordin et al. (2021).

Fossil fuel

The initial fuel use per region is based on the average 2014 to 2018 level of fossil liquid fuel that on municipality level (Swedish Energy Agency, 2020) shown in Figure 1, and divided into diesel and gasoline based on national average shares from (Swedish Energy Agency, 2020). The price of fossil fuels are assumed equal across the country and are prices including taxes and tariffs (Swedish Energy Agency, 2019b). The fuel elasticities e_h are long run own price elasticities for gasoline and diesel from table B1 in Tafesse Tirkaso and Gren (2020). Costs in EUR 2019 for each cost level is based on the elasticity formula

$$e_h = \frac{y_h / y_{k,h}^0}{\Delta p_h / p_k^0} \rightarrow p_h = \frac{y_h p_k^0 / y_{k,h}^0}{e_h} + p_k^0$$

The fossil fuel is divided into five segments, so that each cost segment y_h cover 20% of the total current fuel in the region (i.e., the 20% first reduction has the same cost, after, the 20-40% reduction). The costs are based on the calculated cost at the middle of the segment (e.g. at 10% reduction). The same is done for fuel increases. The fuel volumes are converted to energy equivalents, given conversion coefficients Swedish Energy Agency (2017).

Abandoned land

The amount of abandoned land is uncertain, and has an uncertain development, but the trend is increasing. A low and a high estimate of abandoned agricultural land is studied. The first is from Olofsson and Börjesson (2016) who estimate the area of abandoned land to be 88,000 ha in Sweden. The high estimate is from simulations with the GLOBIOM model (Frank et al., 2011). For a scenario with zero carbon price and climate effects, the estimated area of abandoned land is 543000 ha in Sweden in 2050. To distribute the abandoned land over Sweden, changes in agricultural land per municipality as reported in national statistics between 2010 and 2020 (Swedish Board of Agriculture, 2021) are used, and then distribute the total areas according to their share of total abandoned land. Costs for conversion of land to bioenergy grass cultivation are equal for all regions, but different for the cost categories (Havlik et al. 2011). The cultivation costs from Panoutsou (2017) are estimated for per tonne feedstock for low productivity land, at county level, and equal for all cost categories. Costs for using abandoned land ranges from EUR 160 to 350 per ton dry matter feedstock. The yield per hectare is also from Panoutsou (2017). Figure 2 below shows the resulting total amounts of available feedstock into the three cases, No abandoned land (No AB), low estimate abandoned land (Low AB) and high estimate of abandoned land (High AB).

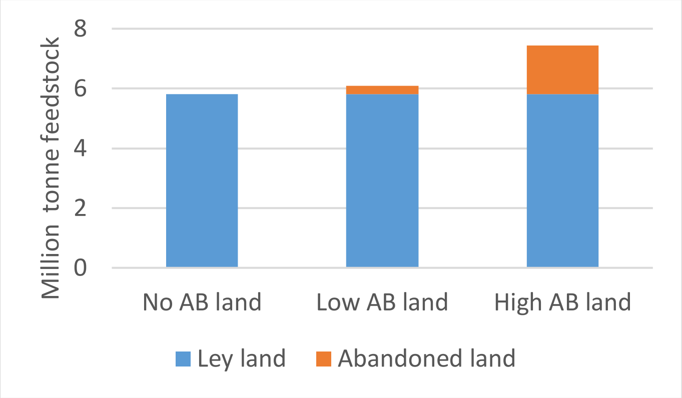

Figure 2 Feedstock availability, Sweden, million tonnes feedstock.

Land use change emissions

For the different assumptions on abandoned agricultural land carbon stock levels at NUTS2 regional level, in t CO_2 per ha, are used. The change in carbon stock is annualized based on a 20-year period. The base assumption is that the land goes from natural vegetation to grassland, which causes emissions. The other assumption is that land goes from cropland to grassland with negative emissions, and the mix assumes that 50% of land goes from cropland and 50% goes from natural vegetation, with small emissions with ambiguous signs (Ruesch and Gibbs, 2008).

Results

Scenarios

Below the scenarios that are analyzed with the model are described. The main objectives are twofold: to study the impact of a climate target rather than a production target, and to study the implications of using abandoned agricultural land for biofuel production. The scenarios are described in the text, and details given in the table.

Abandoned agricultural land (AB land)

In the first set of scenarios (No AB Prod, Low AB Prod, High AB Prod), where AB stands for abandoned agricultural land, a production target at 1050t m3 ethanol per year is used, and three assumptions on available land: none, low estimate and high estimate. The low and high are used as there are uncertainty on how much abandoned land there are available, and also how much there will be in the future. This gives us a span.

GHG target vs production target (GHG targets)

In the second set of scenarios (No AB GHG, Low AB GHG, High AB GHG, No AB 35%GHG, High AB 35%GHG), the same set of available abandoned land as in the first set is used, but now the target is to reach a GHG emission reduction target. The first GHG reduction target is set to equal the emission reduction achieved in No AB Prod. The second GHG reduction target is based on targets for emissions reduction in current policy. Sweden has a policy of emissions reduction in the transport sector by 70% until 2030. As the focus is on ethanol production, the reduction in gasoline emissions is used. The target level is 35% (half target), as it could be assumed electric cars would fill one part of mitigation.

Land use change assumptions (LUC assumptions)

With uncertain carbon stock changes, there is a set of scenarios exploring the effect of the assumption on initial land class of abandoned agricultural land, changing m in $\Delta\vartheta_{a,g,m}$. In the initial scenarios, it is assumed the initial state *m* is *nat,* "natural vegetation". In these scenarios, it is assumed it cropland *crop,* or *mix,* a mix of 50% natural vegetation and 50% cropland. These assumptions are tried with the 35% reduction scenario, and the GHG target as in production targets, with assumed abandoned land to be as in High AB scenarios (High ABmix Prod, High ABcrop Prod, High ABmix ProdGHG, High ABcrop ProdGHG, High ABmix 35%GHG, High ABcrop 35%GHG,).

Table 1 Scenario overview

Scenario set	Scenario	Target	Abandoned land assumption
AB land	No AB	1050t m3 ethanol	No AB land
	Low AB	1050t m3 ethanol	Low estimate
	High AB	1050t m3 ethanol	High estimate
GHG targets	No AB GHG	Emissions in No AB Prod	No AB land
	Low AB GHG	Emissions in No AB Prod	Low estimate
	High AB GHG	Emissions in No AB Prod	High estimate
	No AB 35%GHG	35% of gasoline GHG	No AB land
	High AB 35%GHG	35% of gasoline GHG	High estimate
	Low AB 35%GHG	35% of gasoline GHG	Low estimate
LUC assumptions	High ABmix	1050t m3 ethanol	High estimate, LUC from mix cropland and natural vegetation
	High ABcrop	1050t m3 ethanol	High estimate, LUC from cropland
	High ABmix ProdGHG	Emissions in No AB Prod	High estimate, LUC from mix cropland and natural vegetation
	High ABcrop ProdGHG	Emissions in No AB Prod	High estimate, LUC from cropland
	High ABmix 35%GHG	35% of gasoline GHG	High estimate, LUC from mix cropland and natural vegetation
	High ABcrop 35%GHG	35% of gasoline GHG	High estimate, LUC from cropland

Main results

Overall, facility locations are quite stable for different scenarios. Abandoned land is used due to its low costs. To reach a GHG target when no abandoned land is available, less ethanol than with a production target is produced, while reducing fuel use somewhat to decrease emissions instead. When abandoned land is available, this is used and total production increased in the GHG target scenarios, despite high LUC emissions.

The results are presented set by set, so that the same type of graphs will reoccur for each scenario set.

Abandoned agricultural land level

First, the impact on allowing use of abandoned agricultural use is shown. Figure 3, to the left, shows the number of high and low capacity production facilities, and their respective capacites. It shows that the production facilities are similar: one low capacity and three high capacity facilites. Figure 3, to the right, shows total costs in the scenarios, divided into cost types. Fuel change cost is negative as this includes the avoided costs for gasoline purchase. Total costs are lower with abandoned land, which is due to the lower feedstock costs. As some of the ethanol production gets cheaper than gasoline costs in the high abandoned land scenario, total costs even get negative.

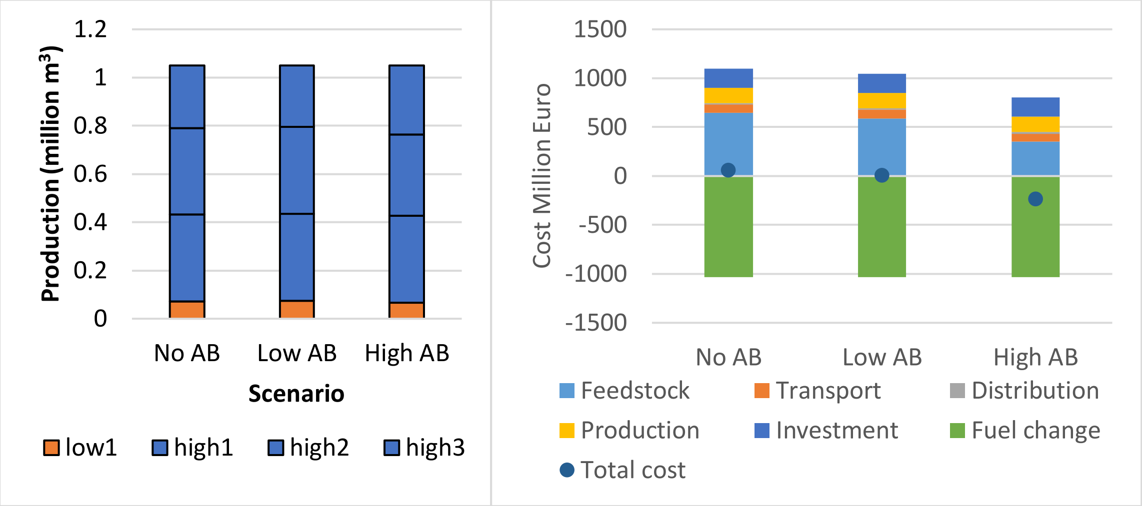

Figure 3 AB land scenarios. Left: Total production divided by the number, type (low or high) and production capacity of facilities. Right: Total costs (dots), divided into cost categories of the supply chain.

Looking at the maps in Figure 4, the three to the left show facility localization and feedstock uptake (in feedstock per hectare, with darker green indicating more feedstock use) from agricultural land, while the two to the left shows feedstock uptake of abandoned agricultural land. The facilities are the blue squares and triangles, and are at stable locations, but the feedstock uptake is different. In both the low and high estimate of abandoned land, almost all abandoned land is used, but less in the low estimate as there is less available abandoned land. This also shows in particular in the high estimate of abandoned land where the feedstock from other agricultural land is clearly lower than in the scenario with no abandoned land.

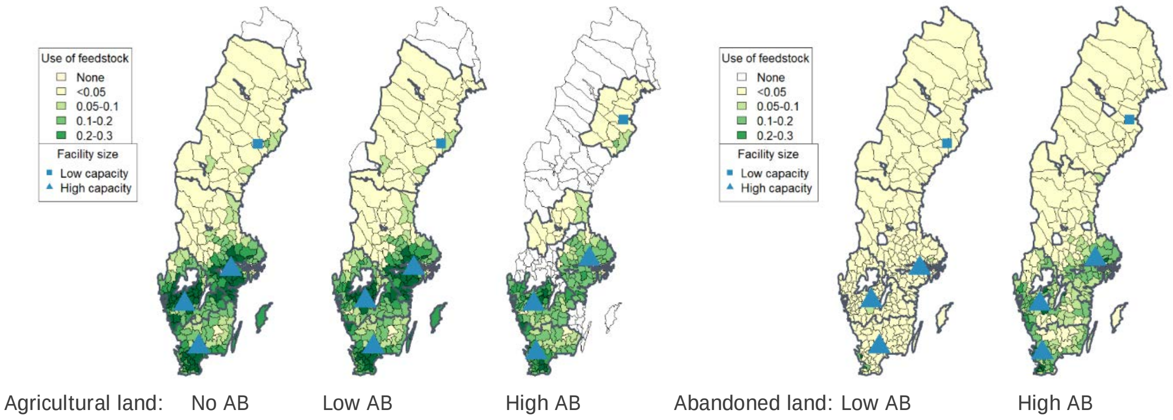

Figure 4. AB land scenarios, facility and feedstock location.

Emissions are emitted in the scenarios, but there is also reduction in emissions as the ethanol is blended into the gasoline, even though there is no climate target. For the same production levels in the three scenarios, total emissions are higher in the abandoned land scenarios, and this is due to LUC emissions. See figure Figure 5, where the light blue represents LUC emissions.

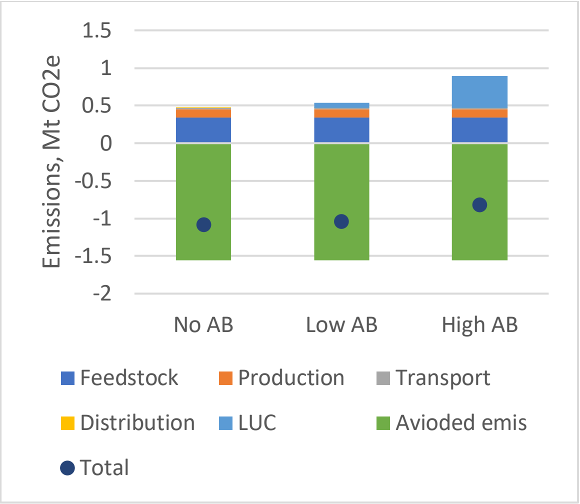

Figure 5 AB land scenarios, total emissions (dots), divided into emission categories.

GHG target vs production target

For these scenarios the results for no abandoned land and the high estimate are shown as these show most differences. Results for the low estimate of abandoned land can be found in the Appendix A2. Comparing the outcomes of a production target with the equivalent GHG target, the GHG target scenarios has differing production levels, with more ethanol production with more abandoned land. This is shown in Figure 6, in the four first staples. Here there are more facilities for the abandoned land case. Comparing the first two (production target) and third and fourth (GHG target) maps in figure x, it is visible that when there is no abandoned land and a GHG target, less feedstock is used than with the production target, in particular less of the most expensive feedstock category. The localization is almost the same. In the abandoned land case, feedstock uptake is now higher than in the production target counterpart, to cover higher production, but abandoned land use is slightly lower. The maps in Figure 7 below show use of abandoned land, where in both cases almost all abandoned land is used.

In the scenarios with more ambitious climate targets (35% decrease of gasoline emissions, shown in the last two staples in Figure 6, and the last two maps in Figure 7), the production levels are slightly higher than the lower GHG target counterparts. All the abandoned land feedstock was already exhausted at the lower target levels, but instead more of feedstock from agricultural land is used.

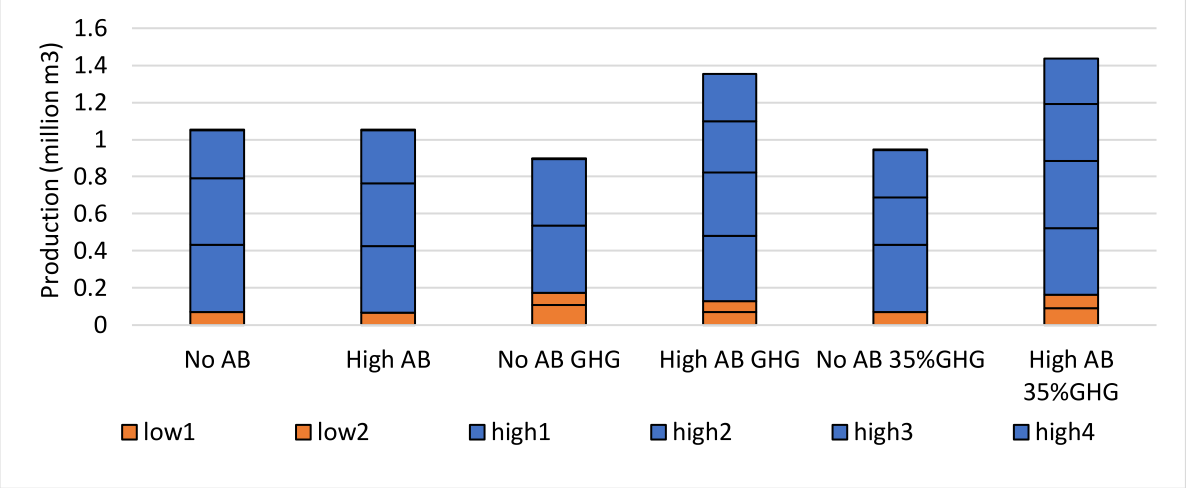

Figure 6 GHG target scenarios. Total production divided by the number, type (low or high) and production capacity of facilities.

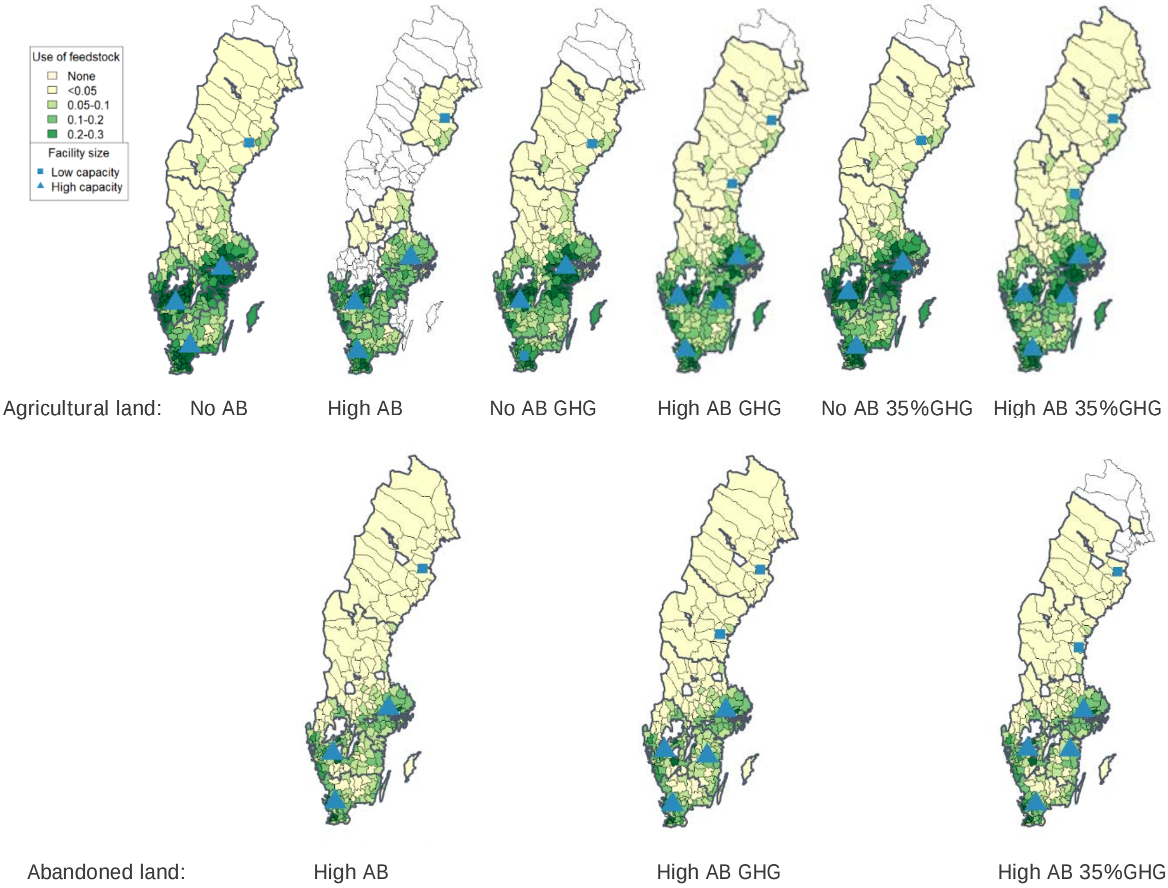

Figure 7 GHG target scenarios, facility and feedstock location.

In Figure 8, total costs per scenario are shown, and in figure x changes in use of different fuels. Total costs are very similar for production and GHG targets, but the constitution is different. For the no abandoned land scenario, there was lower production with the GHG target. Here costs connected to production are smaller. Looking at the Figure 9 on fuel use changes in ethanol, gasoline, and the total blend are shown. Consumption of ethanol increases, but gasoline consumption decrease slightly more, with a net decrease in consumption as a result. Thus, the fuel change costs increase. In total, it is slightly cheaper with the GHG target. For the abandoned land scenarios, ethanol production costs are higher, but the decrease in total fuel consumption is lower, and thus less cost for fuel change. With the more ambitious targets, costs are higher, in particular for feedstock in the no abandoned land scenarios, and more consumer loss costs. In these scenarios, a much larger part of mitigation comes from decrease in total fuel use, as the alternative would be biofuel production with much more expensive feedstock.

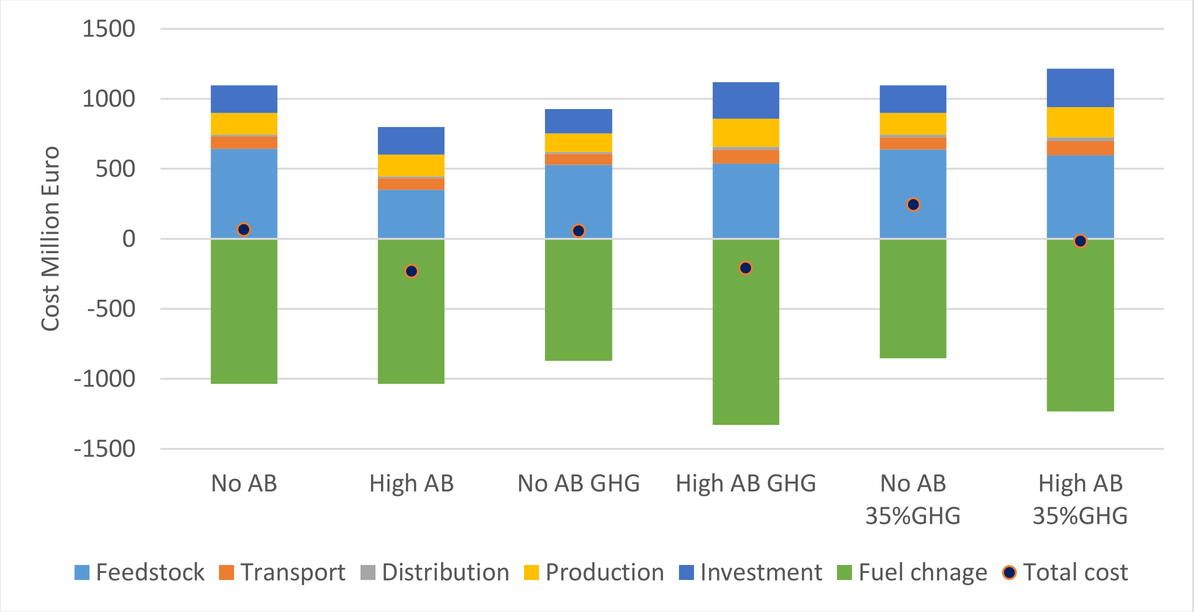

Figure 8 GHG target scenarios, total costs (dots), divided into cost categories of the supply chain.

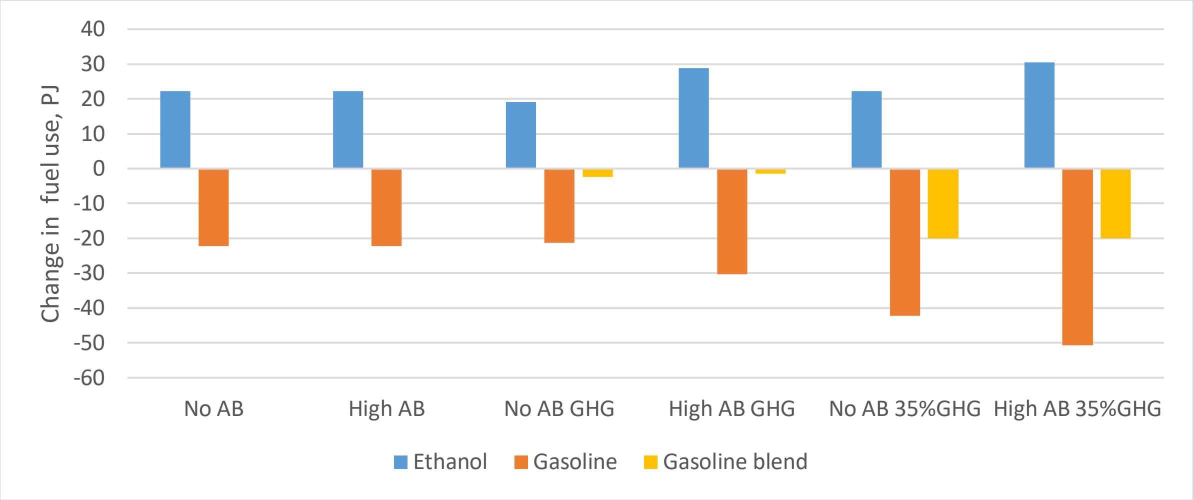

Figure 9 GHG target scenarios, change in fuel use.

Explanations to these outcomes are both costs and emissions. Figure 10 shows emissions, with the total emissions net of gasoline emission reduction depicted with blue dots. Total emissions are equal in the GHG target scenarios as they have the same target, but the constitution differs. Comparing the no abandoned land scenarios, with the GHG target, ethanol emissions are smaller due to the lower production, but also the avoided emissions are smaller. However, there was a total decrease in fuel, which means the abatement option to decrease emission by decreasing fuel use is used, as this has been least costly. For the abandoned land scenarios, ethanol emissions are higher for the scenario without abandoned land, but also avoided emissions from gasoline. In total, the abandoned land scenarios use less of the abatement option to decrease fuel than the scenario without abandoned land. They also have LUC emissions, which increases the ethanol production emissions, but the low costs of abandoned land feedstock makes this an efficient abatement choice anyway.

For more ambitious targets, emissions are lower due to much less gasoline use, while the ethanol emissions increase slightly.

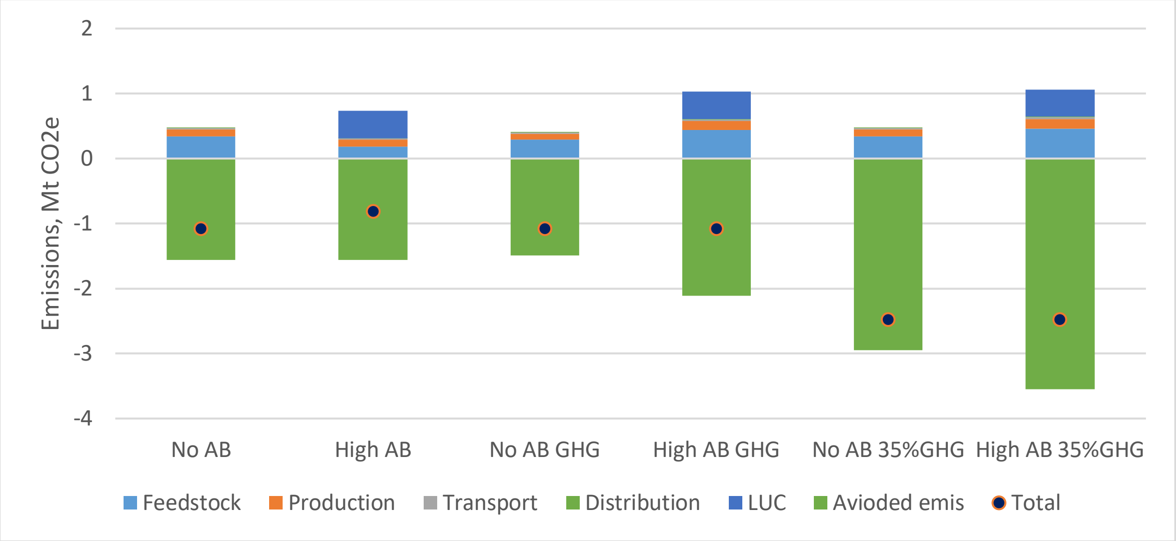

Figure 10 GHG target scenarios, total GHG emissions (dots) divided into emissions categories.

LUC assumptions

The assumptions on land use change (LUC) emissions related to abandoned agricultural land were varied with assumptions of abandoned land classified as cropland (crop), or a mix of cropland and natural vegetation (mix), to account for the uncertainty and different outcomes on emissions. In Figure 11 results on production are shown for the high estimate of abandoned land, for a production target, a climate target based on the production target and thirdly on the more ambitious climate target. Production in the production target scenarios do not change, as they do not depend on emissions. For the low climate targets, production is lower than with base LUC assumption, as the ethanol now gives rise to lower emissions, or even about zero emissions in the LUC crop scenario (see Figure 12 on emissions), and thus less ethanol is needed to decrease emissions. As less ethanol is needed, the targets can be reached at less total costs (Figure 13 on costs). There is no net fuel change (see figure x on fuel changes), instead all mitigation is through substitution.

For the higher GHG target, more ethanol is produced than with the base assumption. Again, the abandoned land gives more mitigation than with the base assumption, and the model results show that it is best to produce some more ethanol rather than reducing fuel use (Figure 14), with lower costs (Figure 13).

With the mix assumption, results are in general in between the results for the assumption of abandoned land being natural vegetation and being cropland, while closer to the cropland option.

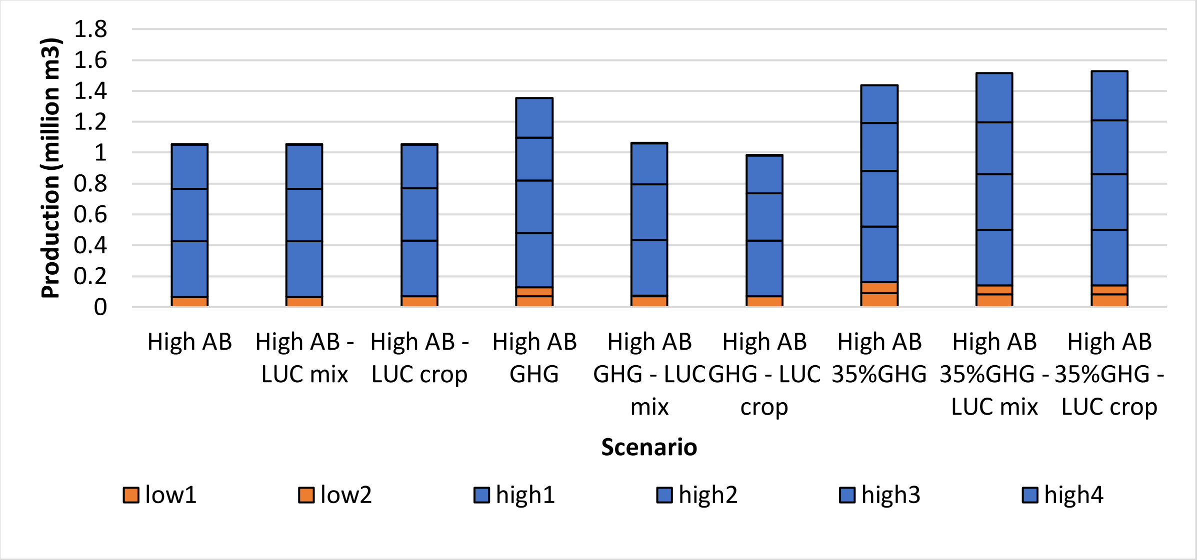

Figure 11 LUC assumption scenarios. Total production divided by the number, type (low or high) and production capacity of facilities.

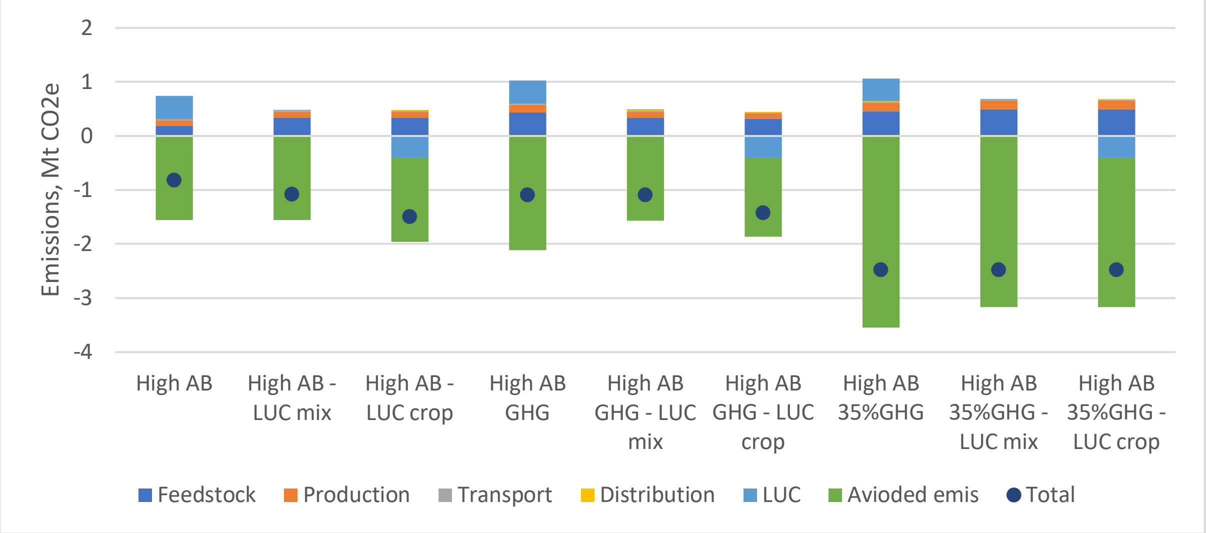

Figure 12 LUC assumption scenarios, total GHG emissions (dots), divided into emission categories.

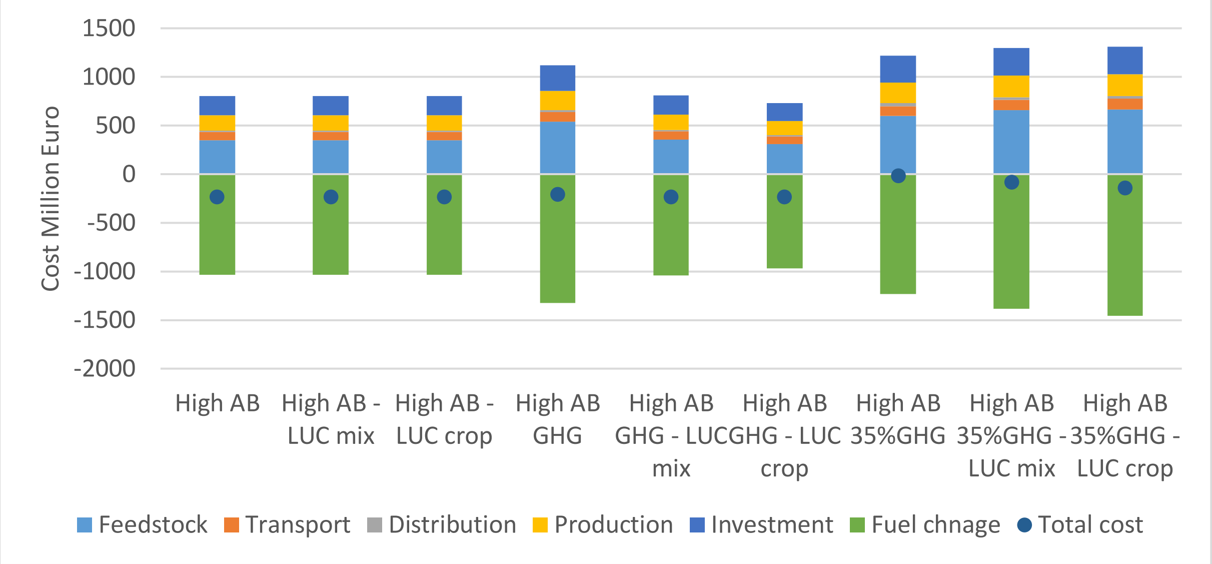

Figure 13 LUC assumption scenarios, total costs (dots), divided into cost categories of the supply chain.

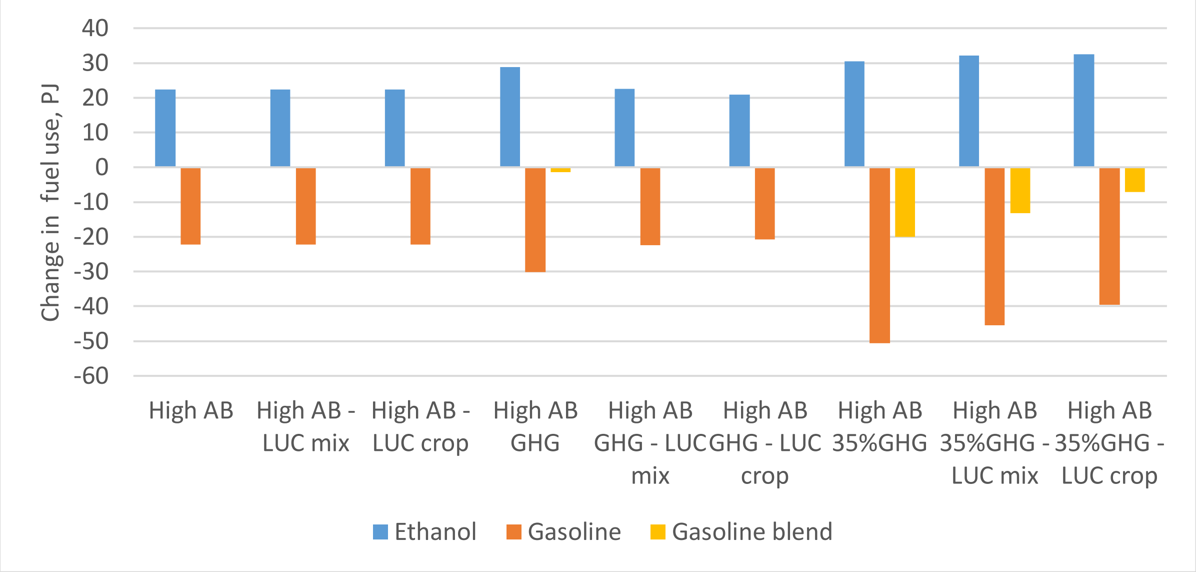

Figure 14 LUC assumption scenarios, change in fuel use.

Sensitivity analysis

To test whether the results were sensitive to the costs of using abandoned land, which were rather low feedstock costs for abandoned land were doubled for the scenario with GHG target based on the production target, looking at the high estimate of abandoned land. Total costs increased, but it was still optimal to use all abandoned land, and thus the results regarding ethanol production and facility localization did not change.

The piecewise linear function representing fuel demand was rather coarse, with three cost levels. To test the impact of this, the length of the segments were halved (i.e. 10 segments of the possible decrease down to zero fuel use). This resulted in lower ethanol production in the scenario with GHG target based on the production target and high estimate of abandoned land. Instead, net fuel use decreased more. The facilities were fewer but at similar places, and similar distribution of feedstock uptake. For the more ambitious climate target, ethanol was higher than with the coarser function, but the difference much smaller. This implies the modelling of cost is important, but at the spatial distribution of the results are not affected.

Discussion

Summary and discussion of results

The report set out to investigate the impact of using abandoned agricultural land for biofuel production, and the role of a GHG reduction target versus a biofuel production target as a policy. For this, a spatial biofuel facility localization model was used, with land use and fuel demand explicitly modelled.

The model simulations showed that in the case study region Sweden, if allowed, the relatively cheap abandoned agricultural land was used to a large extent, to reach an ethanol production target. This decreased the costs and use of other agricultural land, in particular for a high estimate of abandoned land area. This did not affect the localization of biofuel production facilities, and does thus not in itself imply that the strategy for investment should be any different. The use of abandoned land leads to less use of agricultural land and potential competition. A problem is that it implies more GHG emissions due to LUC emissions, if one assume a long time abandonment of the land. With assumptions on the abandoned land that is a land class closer to crop land, emission reductions are considerably larger.

A climate target showed more efficient than a production target at a modest GHG reduction level, corresponding to the production target. Without abandoned land, ethanol production was lower with the GHG target, and somewhat lower ethanol production costs followed, but instead more costs for loss in consumer surplus for decreasing total fuel use. This implies some efficiency of using ethanol for GHG mitigation. With the abandoned agricultural land available as a GHG mitigation option, the ethanol production was higher than for the production target, despite LUC emissions. These low feedstock costs were low enough to induce more ethanol production and gasoline substitution, rather than only reducing fuel use. This implies use of abandoned land is a good way to improve cost-efficiency of biofuel production, despite high emissions. With a LUC assumption with lower or even negative carbon stock changes, ethanol can be even more cost efficient. Therefore, regional characteristics of carbon stock becomes important to consider in policies.

For more ambitious climate targets, i.e. half of the 70% transport emissions decrease target to 2030, more ethanol was produced, but the largest share of emission decrease came from larger decrease in total fuel use. All abandoned land was used, and therefore more ethanol production could only be realized with the more expensive segment of feedstock – thus, eventually the cheaper alternative was to decrease fuel use and shows that the efficient use of ethanol is limited.

The abandoned land is the preferred feedstock land and would in our scenarios be used in the whole country before other land types. Non-abandoned land would mainly be used closer to the facilities, so in the south, in the southwest, and the east of Sweden. Despite the higher total ethanol production in the climate target scenario, feedstock use from non-abandoned land was lower than with the production target, and therefore gave less impact on the livestock sector. This held also when only non-abandoned land was used, as total ethanol production was lower then. With LUC assumptions with lower or negative emissions, even less ethanol and thus less land for fodder production was used.

Limitations

The focus is on abandoned agricultural land and climate targets, but more detailed data on abandoned agricultural land, its extent and carbon stock would increase the accuracy of results. To shed light on this high and low estimate of abandoned land were shown. However, this still misses some of the possible regional differences (e.g., if some regions have abandoned agricultural land with higher carbon stock and others have lower carbon stock, then this would affect the emissions and thus choices), which could be a problem.

Only one type of biofuel is modelled, to simplify the understanding of the mechanisms behind the results. More detail in technologies and facility types could however allow for more diversification in results for facility localization, and could imply changes in fuel consumption too.
Biofuels are traded in the world, whereas our model is a closed economy. Opening up the model for trade would show both possibilities to export for extra revenues, and importing at lower prices or less emissions.

Next steps

Future steps are to address some limitations of the current study. That is, implementing finer data on agricultural land and abandoned agricultural land, and more detail and qualitative differences in technologies. The results of the model have policy implications, and to make these more precise, assessment of efficient economic policy measures for biofuel production can be included. The model should also be extend to cover EU level effects, and analyze policy options at EU level. Then trade could be addressed, which also can cover carbon leakage effects that might have to be addressed. In addition, biofuel production might have impact on other sustainability factors, which will be addressed in coming studies.

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Appendix

A1. Method fuel use change costs

To derive equation (7), the fuel use change cost, net of ethanol production costs, costs from three parts are considered. For fossil fuel producers, their change in revenue depends on their price, and quantity gasoline sold, but costs decrease with the same amount:

$$\sum_{k\in\widetilde{K''}}\left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} p^0_k d\hat{y}_{k,h}\right)-\sum_{k\in\widetilde{K''}}\left(\int_{y^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} p^0_k d\hat{y}_{k,h}\right)=0$$

Biofuel producers have the cost for ethanol production, but also revenues from selling biofuel at blend in prices:

$$\sum_{k\in\widetilde{K'}}\left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} p^0_k d\hat{y}_{k,h}\right)$$

The consumers have a change in consumer surplus from changed fuel consumption. Their cost for fuel purchase also changes with fossil fuel and biofuel consumption:

$$\sum_{k\in\widetilde{K'''}}\left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} D^{k,h}\left(\hat{y}_{k,h}\right)d\hat{y}_{k,h}-\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} p^0_k d\hat{y}_{k,h}\right)$$

The total cost is thus:

$$c_h^{FUEL}=-\sum_{kk\in\widetilde{K'''}}\left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} \left(D^{k,h}\left(\hat{y}_{k,h}\right)-p^0_k\right)d\hat{y}_{k,h}\right)-\sum_{k\in\widetilde{K'}}\left(\int_{\hat{y}^0_{k,h}}^{\hat{y}^0_{k,h}+\hat{y}_{k,h}} p^0_k d\hat{y}_{k,h}\right)$$

A2. Results

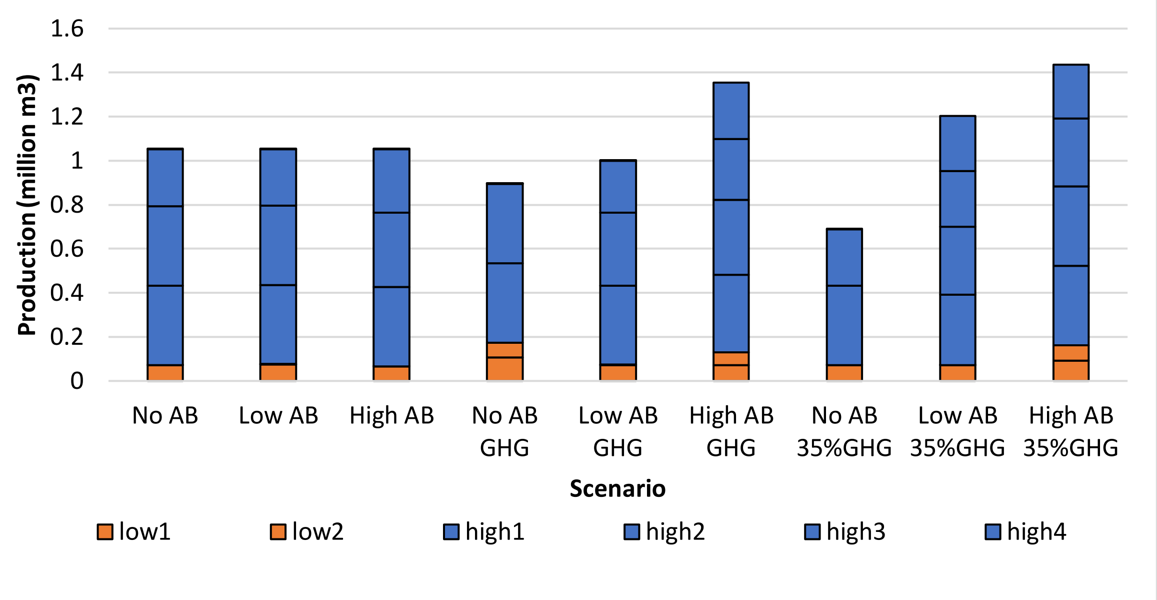

Figure A 1 GHG target scenarios. Total production divided by the number, type (low or high) and production capacity of facilities.

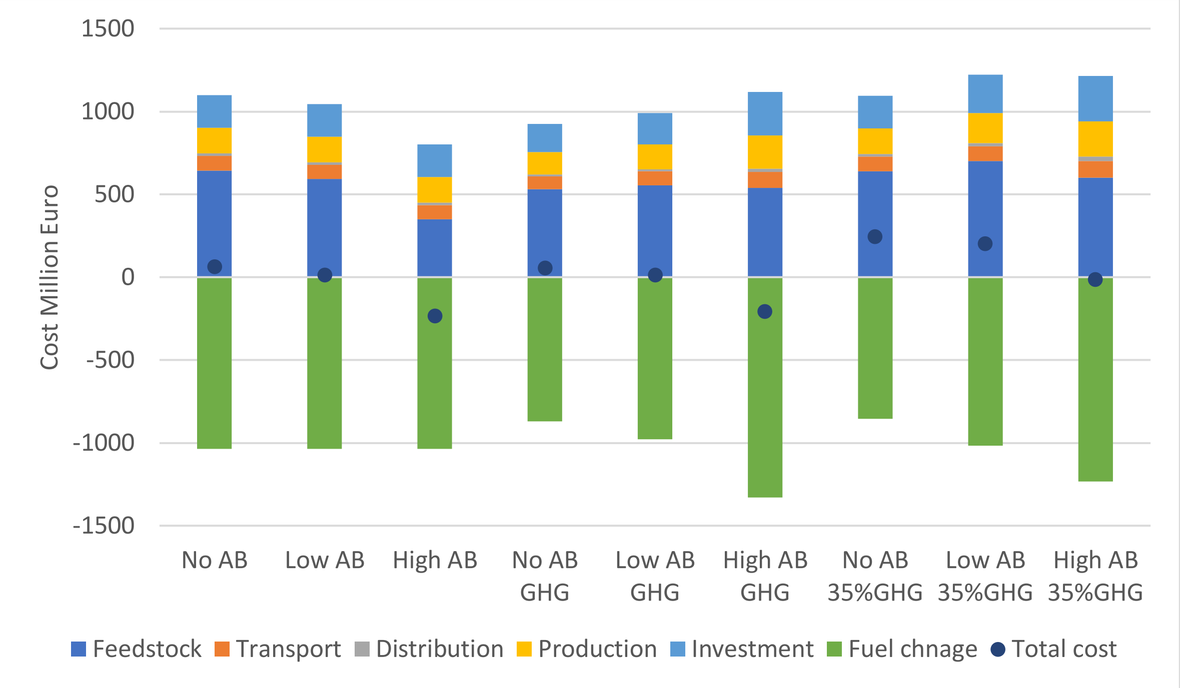

Figure A 2 GHG target scenarios, total costs (dots), divided into cost categories of the supply chain.

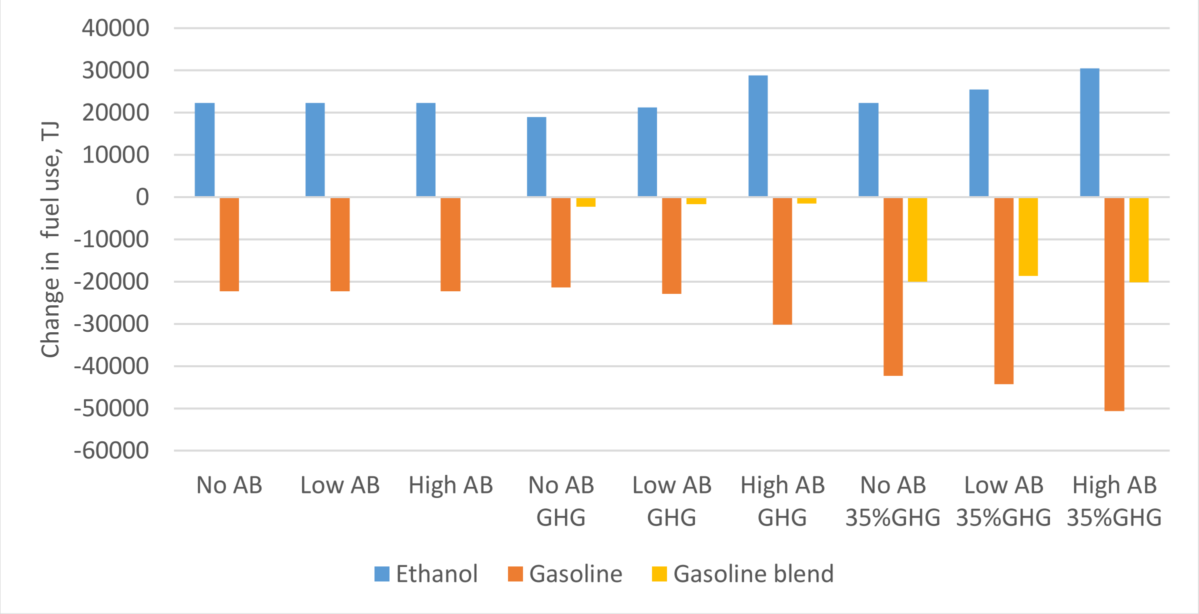

Figure A 3 GHG target scenarios, change in fuel use.

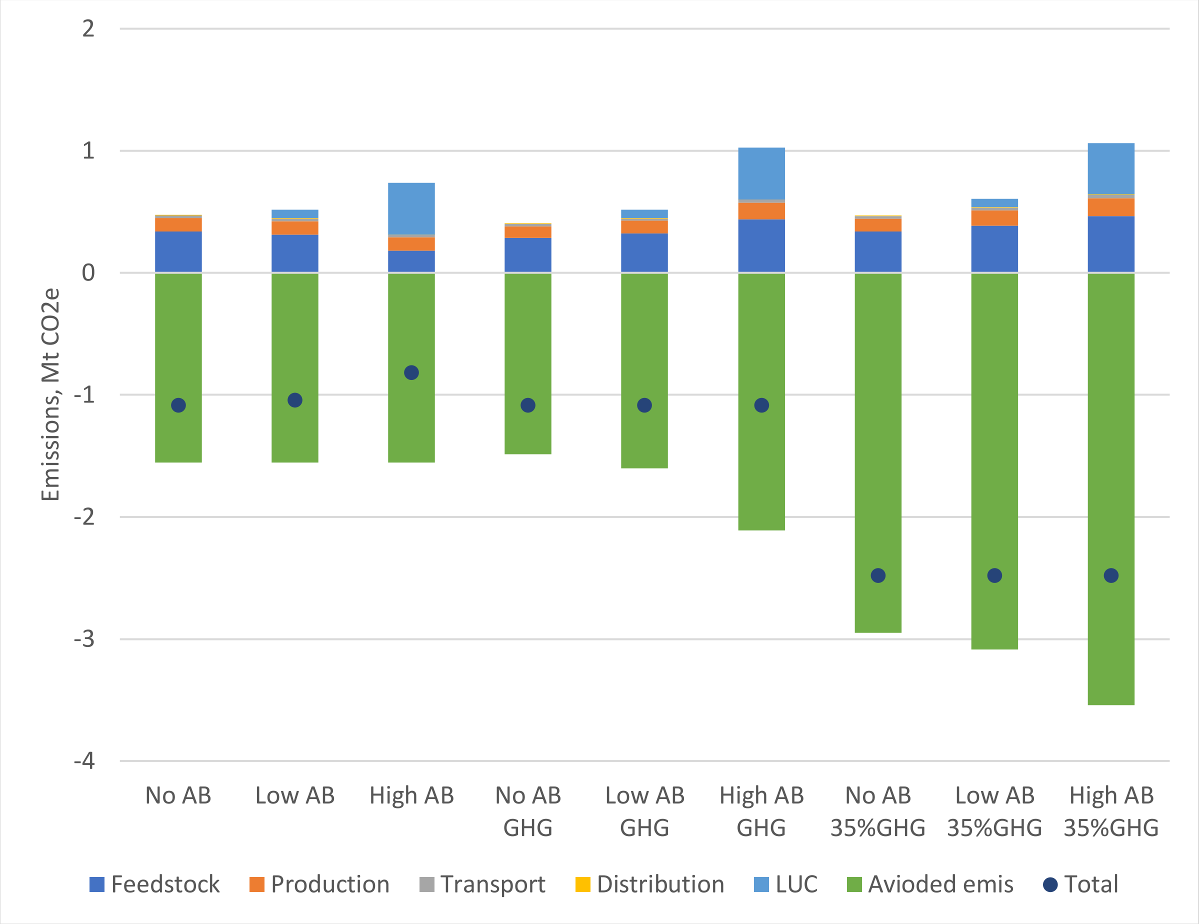

Figure A 4 GHG target scenarios, total GHG emissions (dots) divided into emissions categories.