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Cost-effective reductions in greenhouse gas emissions: Reducing fuel consumption or replacing fossil fuels with biofuels

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ABSTRACT

Greenhouse gas emissions from the transport sector can be reduced by decreasing fuel use by different means, and by blending biofuels into fossil fuels. A cost-effective combination of these measures is determined by spatially specific characteristics such as fuel demand, feedstock production costs, and greenhouse gas emissions from the feedstock production. We developed a spatially explicit model to explore the role of reduced transport fuel use and increased use of domestically produced biofuel, respectively, in a cost-effective policy for greenhouse gas abatement. The model is applied to domestic lignocellulosic biofuel from agricultural land, gasoline, and diesel for road transport in Sweden. The results show that the use of biofuel is particularly cost-effective under low and modestly stringent abatement targets. For more stringent targets, decreased fuel end use dominates the abatement portfolio. Replacing the emissions target by a biofuel production target increases the marginal cost of reducing emissions by up to 250%. With the current vehicle fleet, technical constraints on blend-in possibilities limit the role of biofuels at higher target levels.

1. Introduction

The transport sector covers 20% of greenhouse gas (GHG) emissions globally (Olivier and Peters, 2020). Hence, a range of different abatement measures are needed to reduce emissions from the transport sector and comply with the Paris Agreement. Many policies target either replacement of fossil fuel with biofuels, or reductions in the overall fuel consumption. The former has proven to be technically convenient to implement as in many cases biofuel can be blended with fossil fuels for use in existing vehicles (Sims et al., 2014). The latter can be achieved through reducing transports, shifting to more fuel-efficient vehicles, and changing transport mode.

In the European Union, EU, the transport sector is expected to contribute to the target to reduce total GHG emissions by 55% by 2030, relative 1999 levels and be carbon neutral by 2050 (European Commission, 2021). New light vehicles must be emission free by the year 2035 (European Parliament and Council of the European Union, 2023). To achieve this, the EU Commission's Sustainable and Smart Mobility strategy states that cars should be zero-emitting by 2050, that there should be a shift toward public transport, and that freight should move from road to rail (European Commission, 2020). To increase biofuel for transport, there are several regulatory measures, including blend-in quotas, tax exemptions, and, to lesser extent, subsidies (Banja et al., 2019).

Increased domestic biofuel production can be a cost-effective alternative to reduce GHG emissions, particularly when considering the growing global demand for biofuel with fewer options for imports (IEA, 2021). Currently, most of the EU's biofuel consumption is covered by domestic production of first-generation biofuels, i.e., using food crops as feedstock (Flach et al., 2022, pp. 3-5). To increase the sustainability of biofuels, the EU restricts the increase of first-generation biofuels as they compete with food production (European Parliament, 2018). This highlights the need to evaluate second-generation biofuels made from, e.g., perennial bioenergy crops, which cause less competition. In addition, domestically produced biofuel reduces the dependence on imported fossil fuels, which has proven risky since the Russian aggression towards Ukraine in early 2022 and the increase in fossil fuel prices that followed (Ari et al., 2022, pp. 4-5).

Abatement of GHG emissions in the transport sector is costly: biofuel prices are still not competitive; electric cars and more fuel-efficient vehicles require investments; and reduced transports and changes in travelling mode can reduce consumer surplus. Economic theory shows

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that the cost-effective combination of different abatement measures is determined by their relative marginal costs in combination with their emissions (Baumol et al., 1988, pp 36-47). The spatial configuration of fuel consumption and biofuel production is of major importance for the costs of the measures mentioned; hence a spatial model is necessary to determine the cost-effective allocation of abatement efforts.

The land that can be used for biomass production is finite and varies across space. Increased feedstock outtake implies increased competition between biofuel and other land uses, thus increasing marginal costs. There are also considerable investment costs for large production facilities, and costs for the transport of biomass and biofuel (Nordin et al., 2021). This implies a trade-off between transport costs on the one hand, and economies of scale for facilities on the other, a type of problem first discussed in the context of a von Thünen model approach (Wood and Roberts, 2010, pp. 16–19). Moreover, despite biofuels' function as a replacement for GHG intensive fossil fuels, biofuel production processes give rise to spatially variable carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from feedstock cultivation, transports of feedstock and biofuel, and biofuel production facilities. Finally, the costs of reduced fuel consumption vary across space depending on the locally specific price elasticity of fuel demand (Tirkaso and Gren, 2020).

The purpose of this study is to investigate cost-effective strategies for reaching a GHG emissions reduction target in the transport sector. We compare the option of blending-in second-generation domestic biofuel, to that of reducing transport fuel use, taking into account that the transport fuel could be a blend of fossil fuels and biofuels. Moreover, we compare the results under a GHG emission target to those under a biofuel production target.[1] The comparison of targets is motivated by the fact that policies for biofuels are often based on targets for biofuel use, e.g., mandatory blend in quotas (Banja et al., 2019). In contrast, economists recommend the use of an emissions reduction target combined with carbon pricing, due to the higher cost-effectiveness.

To examine these issues, we develop a spatially explicit model for transport fuel consumption, second-generation biofuel production on agricultural land, and fuel blending. The model is applied to the road transport sector in Sweden and considers diesel, gasoline, and biofuel consumption. We abstract from trade in biofuel, motivated by our aim to examine the role of spatial interaction across smaller spatial units. The focus on biofuel for transports is motivated by the expected development of the transport sector where a first step is expected to be a switch to biofuels and more efficient combustion engines, followed by a later phasing-in of more electric cars and increased transport efficiency (Swedish Climate Policy Council, 2020; Kyriakopoulou et al., 2021).

The economics literature relevant to our research question is that on carbon abatement strategies for the transport sector. For instance, Haasz et al. (2018) use an economy wide model to identify the cost-effective role of the transport sector for large-scale emissions reduction in the EU, finding a limited role of the sector in the short term but a larger role in the long term as the current vehicle fleet is replaced with electric vehicles. Others study the only the transport sector, e.g., Mercure et al. (2018) use a global dynamic least-cost simulation model for bioenergy, which includes endogenous technological learning and investments in production facilities. They conclude that the Paris Agreement can be reached with a mix of policies.

Several studies focus on biofuels. Millinger et al. (2018) optimise the mix of different biofuel technologies and their development over time for an exogenously given level of total biofuel demand in the transport sector. Nordin et al. (2021) investigate the cost-effective localization of biofuel production using a spatial economic model. Using an integrated fuel and agricultural model, Lee et al. (2023) show that a carbon tax applied in the US could decrease global transport emissions, but the contribution of biofuel would be small. A biofuel blend-in requirement could reduce domestic emissions, but a rebound effect on world gasoline prices counteracts the effect on emissions. Results in Ragajopal et al. (2011) and Hill et al. (2016) confirm this rebound effect. Moreover, biofuel expansion and energy policies implies large scale land use changes in one country which can cause indirect land use change in other countries that affect land use change emissions and agricultural prices (Searchinger et al., 2008; Popp et al., 2011). Further, Zilberman et al. (2013) discuss how increased competition with food production can reduce direct emissions from agriculture. The impact on welfare is discussed by, e.g., Kretschmer et al. (2009) who model the impact of the design of EU biofuel use targets on welfare, and Timilsina et al. (2013) who studies the impact of policies for different biofuels for the economy of Argentina. Chen et al. (2021) investigates the effect on welfare from biofuel policies in the US, resulting from different sectors, including social costs for environmental effects. Landry and Bento (2020) find that including additional externalities such as congestion further decrease the welfare loss of biofuel mandates, as these are affected by a biofuel mandate. In a review of biofuel policies, de Gorter and Just (2010) find that although a policy targeting emissions is superior to one directly targeting biofuel, a biofuel blend-in mandate is still superior to biofuel subsidies and can be a complement to suboptimal fuel taxes.

We contribute to the literature through spatial modelling of cost-effective reductions in GHG emissions in the road transport sector by examining the option to blend biofuel in fossil fuel, capturing the interdependence between replacing fossil fuels with domestic biofuel and reducing fuel use in the transport sector. Fuel consumption is linked to a detailed spatial model of biofuel production using a lignocellulosic ethanol technology based on feedstock from agricultural land, representing second-generation biofuels. This allows us to identify the optimal supply of domestically produced biofuel in response to policy targets. The Swedish case study contributes by examining the potential role of the agricultural sector for biofuel production in a country with spatially heterogeneous land use and consumption of fuel. This heterogeneity implies that the localization of biofuel production and fuel consumption matters for the costs and environmental impacts of policies.

The article is structured as follows: the model is presented in section 2, followed by a description of the case study area in section 3 and the data in section 4. This is followed by a description of scenarios in section 5, results in section 6, and discussion in section 7. The paper ends with conclusions and policy implications.

2. Model

We develop a spatially explicit optimization model for transport fuel consumption and biofuel production for a small country. The model is used to minimize the total costs to achieve policy targets for reducing GHG emissions or for biofuel production levels. The emissions reductions are achieved either by replacing fossil fuel with domestically produced second-generation biofuel, or by reducing end use of transport fuel. The model takes a partial equilibrium approach. We abstract from economic impacts on other sectors and from international trade in biofuels and this is therefore a case of autarky in terms of biofuel,[2] which is motivated by the focus on the spatial configuration of domestically produced biofuel and fuel consumption. The application to a small country implies that changes in fossil fuel consumption have no impact on the world market for fossil fuels and biofuel. The interaction of

[1] In our model, a production target for domestic biofuel is equivalent to policies formulated as a mandate for its use.

[2] Given the small country assumption, inclusion of biofuel trade would mainly imply a fixed price for biofuel. This price would change if other countries increase demand for biofuel, as forecasted by the OECD/FAO (2023). To model such price changes in the international market for biofuel, a full-scale fuel trade model which also considers global carbon policies would be necessary, which is outside the scope of the paper. Sweden currently trades in biofuel, but we assume a zero change in trade.

feedstock production and agricultural production is modelled by increasing feedstock costs due to competition for land in each region. The model assumptions imply that the prices of agricultural products other than feedstock are fixed, consistent with a small, open economy. Simultaneous changes in inter-regional trade is only modelled explicitly for biofuel feedstock.

Below, we first describe biofuel production costs, followed by costs for reductions in fuel consumption, and emissions. Then we describe the social planner's decision problem. A complete list of variables, sets and parameters can be found in Appendix A.

2.1. Costs for increased biofuel production and distribution

Biofuel is assumed to be domestically produced on agricultural land. The discrete choice of localization of biofuel production facilities is important for the cost structure. We use the cost-effectiveness model for biofuel production in Nordin et al. (2021), which determines the cost-effective spatial distribution of biofuel production facilities, the uptake of feedstock for biofuel, and the delivery of biofuel to end-users. Here, we give a brief overview of the biofuel production model, the full version can be found in Appendix C.

Investment in a biofuel production facility, $I_{v,i}$ is a discrete choice in each region i, where $i = 1, \ldots, 290$ indicates biofuel production facility locations, covering all the 290 municipalities in Sweden. Each production facility can be assigned a capacity v, with $v = high, low$. The capacity can vary within a given span for each type, and capacity equals production. The associated investment costs, $c_{i,v}^{INV}$, are characterized by economies of scale. Operation costs, c_i^{OP}, and production levels of biofuel, y_i, in each region depend linearly on the feedstock input x_i. The feedstock input at a facility in region i equals the sum of feedstock flows $x_{i,g}^{TR}$ to region i from different supply regions g, with $g = 1, \ldots 290$, indicating the same set of municipalities as i. The total feedstock produced in each region, x_g, is constrained by the maximum area of land available for feedstock production, implying a maximum level of feedstock, $\bar{x}_g$. The total feedstock available for biofuel production at a facility equals the amount of feedstock transported to that facility. The feedstock cost for a production facility, c_i^{FEED}, considers differences in costs for feedstock deliveries from different regions. We assume increasing costs for feedstock production in each region due to competition for land with other crops and grassland.

Transportation of feedstock is assumed to be associated with a linear cost function, $c_{i,g}^{TR}$, that is determined by the feedstock volume, $x_{i,g}^{TR}$, and the distance, $d_{g,i}$, between the regions where the feedstock is produced and the production facility. Similarly, the distribution of biofuel to different end use regions h, with $h = 1, \ldots, 290$, is associated with a linear cost function, $c_{i,h}^{DISTR}$, and is assumed to be dependent on the biofuel volume, $y_{i,h}^{TR}$, and the distance. The relationship between feedstock production and use is assumed to hold with equality. The total countrywide cost for biofuel production and transport is denoted by c^{BIO}, and is expressed as:

$$c^{BIO} = \sum_i \sum_v \left(c_{i,v}^{INV} + c_i^{OP} + c_i^{FEED} \right) + \sum_i c_i^{TR} + \sum_i c_i^{DISTR} \tag{1}$$

2.2. Costs for reducing fuel consumption

We assume that consumers can use different types of fuels for transport: a gasoline-biofuel blend, and diesel.[3] Fossil fuel use can decrease either by decreasing the end use of fuel, or by blending biofuel into gasoline. In the latter case, the gasoline use can decrease while keeping the end use of the blended fuel constant. The costs for transport fuel reductions are measured as reductions in consumer surplus. The use of long run fuel demand functions for the calculation of change in consumer surplus ensures that the resulting cost estimate captures changes in vehicle miles travelled, adjustments in the vehicle fleet, and changes in transport mode. Demand for the gasoline-biofuel blend and diesel are modelled as separable, motivated by model tractability. We assume that the gasoline-biofuel blend is qualitatively equal to gasoline, after correcting for the difference in energy content (Knoll et al., 2009, p. 31). Moreover, we assume a fully elastic supply of gasoline and diesel, motivated by the fact that Sweden is a small country on the international market.[4] Domestic biofuel production, represented by one biofuel variety, is modelled with an increasing marginal cost of supply. All fuel volumes are expressed in energy equivalents.

In the model, we distinguish between the quantities of fuel end use (diesel and the gasoline-biofuel blend), and the quantities of pure fuel (gasoline, diesel, and biofuel) that are delivered to the gas stations and used to form the fuels for end use. The delivered quantities of pure fuel are denoted by $y_{l,h}$ (with initial quantities $y_{l,h}^0$), where l, with $l = bio, gas, die$, denotes pure fuels. The market clearing condition states that all produced biofuel is delivered to the regions h where it is used, i.e.:

$$y_{bio,h} = \sum_i y_{bio,i,h}^{TR} \tag{2}$$

where $y_{bio,i,h}^{TR}$ is the delivery of biofuel from biofuel production facility location i to region h. This equation connects the distribution of biofuel use, $y_{bio,i,h}^{TR}$, to biofuel production in section 2.1.

Quantities of fuel end use are denoted by $z_{k,h}$ (with initial quantities $z_{k,h}^0$), where k denotes fuels for end use, with $k = Bgas, Edie$. Here, $Bgas$ indicates the blend of gasoline and biofuel for end use, and $Edie$ indicates the end use diesel. The quantity of fuel end use in each region equals the amount of delivered pure fuel, such that for the blended fuel we have that:

$$z_{Bgas,h} = y_{gas,h} + y_{bio,h} \tag{3}$$

while end use diesel equals the diesel supplied to the region:

$$z_{Edie,h} = y_{die,h} \tag{4}$$

The share of biofuel in the total amount of the gasoline-biofuel blend, $z_{Bgas,h}$, is restricted by a blend-in cap, γ, reflecting the technological limitations of blending. Therefore, gasoline can only be replaced with biofuel until the cap is reached:

$$y_{bio,h} \leq \gamma z_{Bgas,h} \tag{5}$$

The net cost, c_h^{FUEL}, for a reduction in fuel use is given in Equation (6). The parameter p_l expresses the consumer price of fossil fuel. The first term on the right-hand side (r.h.s.) in Equation (5) then expresses reduction in consumer surplus when the fuel end use decreases, calculated as the integral over the inverse demand function for the *fuel end use*, $z_{k,h}$. This term is positive. The second term is the savings from reduced *fossil fuel* purchases, which is negative.[5]

$$c_h^{FUEL} = \sum_k \int_{z_{k,h}}^{z_{k,h}^0} D_{k,h}(z_{k,h}) dz_{k,h} + \sum_{l \in gas,die} p_l \left(y_{l,h} - y_{l,h}^0 \right) \tag{6}$$

[3] We make the simplifying assumption that there is no production of biofuel to blend in diesel, which is motivated by our focus on lignocellulosic material from the agricultural sector. One can note that the industry that uses lignocellulosic feedstock to produce biofuel for blending in gasoline is more developed than that for blending in diesel (Brown et al., 2020).

[4] This is a simplification as Sweden has a net export of fossil fuels, which are produced from imported crude oil (National Institute of Economic Research, 2007; Swedish Energy Agency, 2019c).

[5] The reduction in fossil fuel purchases can be achieved by gasoline being replaced by biofuel and by reduced fuel end use.

2.3. Emissions

We assume that emissions are linearly related to the different goods and processes. For fossil fuels, we calculate emissions e_h^{gas} and e_h^{die} based on the changes in quantities of fuel and emissions intensities of the respective fuels, denoted ε^{gas} and ε^{die}, respectively:

$$e_h^{gas} = \varepsilon_{gas} y_{gas,h} \quad (7)$$

and,

$$e_h^{die} = \varepsilon_{die} y_{die,h} \quad (8)$$

Emission intensities of feedstock, ε_i^{FEED}, differ regionally based on spatial characteristics such as soil, climate, and landscape characteristics, and the emissions are proportional to feedstock supply x_g. Other biofuel emission intensities are assumed equal across the country: ε^{OP}, ε^{TR}, and ε^{DISTR}, denote emission intensities of production, transport of feedstock, and distribution of biofuel, respectively. The emissions from transports depend linearly on distances in addition to quantities. We then have that:

$$e_g^{FEED} = \varepsilon_g^{FEED} x_g \quad (9)$$

$$e_i^{OP} = \varepsilon^{OP} y_i \quad (10)$$

$$e_{i,g}^{TR} = \varepsilon^{TR} d_{i,g} x_{i,g}^{TR} \quad (11)$$

and,

$$e_{i,h}^{DISTR} = \varepsilon^{DISTR} d_{i,h} y_{i,h}^{TR} \quad (12)$$

Total emissions, e^{TOT}, are then given by:

$$e^{TOT} = \sum_h \left(e_h^{die} + e_h^{gas}\right) + \sum_g \sum_i \left(e_{i,g}^{TR} + e_{i,g}^{FEED}\right) + \sum_h \sum_i e_{i,h}^{DISTR} + \sum_i e_i^{OP} \quad (13)$$

One can note that we model direct emissions, while emissions from indirect land use change are not included, which is motivated by our focus on the trade-off between fuel blending and reductions in fuel use, and the role that the spatial configuration of production of consumption plays in this context.[6]

2.4. The social planner's decision problem

We assume that a social planner strives to meet GHG emissions targets at minimum cost. The annual GHG emissions target E^* is assumed to be set on a national level, and is defined by:

$$e^{TOT} \leq E^* \quad (14)$$

Total costs, c^{TOT}, are defined as the sum of costs for fuel consumption and for biofuel production:

$$c^{TOT} = \sum_h c_h^{FUEL} + c^{BIO} \quad (15)$$

The social planner's decision problem is to minimize the total costs, and can be described as follows:

$$\underset{x_g, x_{i,g}^{TR}, I_{v,i}, y_i, y_{l,i,h}^{TR}, y_{l,h}, z_{k,h}}{\text{Argmin}} \quad c^{TOT} \quad (16)$$

$s.t.$

Eqs. (1)–(15), Eqs. (C.1) - (C.16) in Appendix C,

$$x_g, x_{i,g}^{TR}, y_i, y_{l,i,h}^{TR}, y_{l,h}, z_{k,h} \geq 0$$

$$I_{v,i} \in \{0, 1\}$$

As an alternative to the emission target in equation (13), we also consider the possibility that the policy maker instead sets a national target Y^* for the annual biofuel production:

$$Y = \sum_i y_i \geq Y^* \quad (14)$$

We simulate the model numerically with relevant empirical data described in section 4, using the optimization software GAMS.[7]

3. Case study region Sweden

We apply our model to Sweden, where agricultural land covers 7% of the total land area and is mostly found in the southern and south-eastern parts of the country. The share of arable in total land is illustrated in Fig. 1, panel E. Most of the agricultural land is used for crop production and production of ley for animal fodder (Statistics Sweden, 2020a). Sweden has a total area of 450 thousand km^2 and is divided into 290 municipalities which we use as regional units.

The distribution of the population is similar to that of the agricultural land: the greatest density is in the south and southeastern parts (Statistics Sweden, 2020b). Transport fuel use follows the population and is thus larger in the south and around larger cities, but sparse in the north (see Fig. 1, panel A and B for gasoline and diesel, respectively). In the south, gasoline consumption exceeds diesel consumption, whereas the reverse is true in the north (Statistics Sweden, 2022). For transport fuels as of 2018, 23% of the total volume was bio-based, for which most of the feedstock was imported (Swedish Energy Agency, 2019a).

At present, Sweden complies with the requirement in the EU's renewable energy directive that at least 14% of transport fuel consumption should be from renewables (Swedish Energy Agency, 2019a; European Parliament, 2018). The more ambitious national target to reduce overall greenhouse gas emissions in the transport sector by 70% by 2030 (Government Offices of Sweden, 2017) has not yet been reached. There are mandatory emissions reduction quotas for fossil fuel suppliers that are achieved primarily by blending with biofuels. In addition, there is a tax on CO_2 emissions which applies to fossil fuels.

In the case study, biofuel production is assumed to use reed canary grass, a lignocellulosic material, as feedstock since it can be grown in all of Sweden (Börjesson, 2007). Our data reflect the production of lignocellulosic ethanol. We assume that these data are representative for technologies producing both ethanol and biogasoline.[8] This choice is made since the technology for lignocellulosic ethanol is readily developed, albeit not yet at commercial scale (Brown et al., 2020), and the quantitative potential is large as it uses non-food biomass (Börjesson et al., 2013, p. 174). Moreover, ethanol and biogasoline are relatively

[6] One can note that the magnitude of global emissions due to indirect land use change are uncertain. For example, Ahlgren and Di Lucia 2014 find in a review that the indirect emissions from perennial energy grasses range from -66 to +360 percent of the direct emissions.

[7] We use GAMS version 38.1.0, with the OSICPLEX mixed integer linear programming solver. The model is solved at 0.5% gap tolerance from optimality.

[8] This extension to both ethanol and biogasoline blended into gasoline is motivated as follows. i) Modern gasoline engines could be compatible with a volume blend-in rate of up to 25% ethanol. However, biogasoline can be blended at an even higher rate, and the rate depends on the quality of the fuel (Furusjö and Mossberg, 2020). By using both fuel types, the total blend-in rate is higher. ii) The costs for biogasoline production are predicted to be in the same range, or higher, than those for lignocellulosic ethanol, when lignocellulosic material or ethanol are used as raw material (Furusjö and Mossberg, 2020). Therefore, with the same feedstock and similar costs, we think it is a fair assumption to model ethanol and biogasoline as one representative fuel. This facilitates modelling and allows for the use and production of biofuel from all the feedstock available in the model.

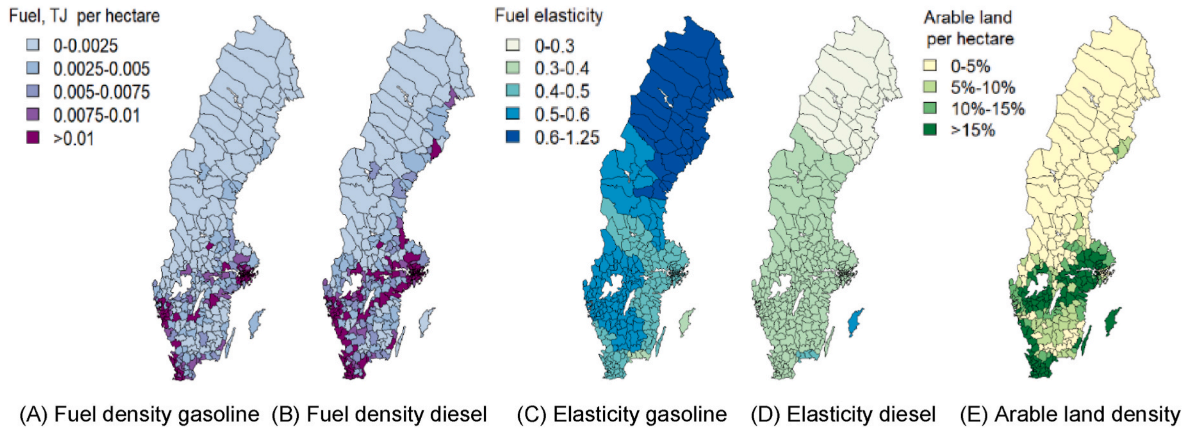

Fig. 1. Background data. Panel A: Fuel density in delivered TJ per hectare, gasoline. Panel B: Fuel density in delivered TJ per hectare, diesel. Panel C: Fuel long-run demand elasticity, gasoline. Panel D: Fuel long-run demand elasticity, diesel. Panel E: Arable land density in percent arable land of total land area.

easy to use in the current vehicle fleet by blending with gasoline.

4. Data

4.1. Fuel and emissions data

The total costs in the model approximate the net private costs, measured as the costs that accrue to Swedish consumers and biofuel producers, and are parametrized with data from Sweden. All costs are measured in EUR 2019. The initial fuel consumption per region, $y^0_{l,h}$, is based on deliveries of annual gasoline and diesel products for road transport to municipalities in 2018. Those include a required share of biofuel (Statistics Sweden, 2022). The fuel use densities measured as TJ fuel per hectare are shown in panel A and B in Fig. 1. The prices of transport fossil fuels, p_l are as of 2019, including taxes and tariffs (Swedish Energy Agency, 2019c), and are assumed equal across the country.[9] We construct the long-run linear demand functions, $D_{k,h}$, based on own-price elasticities and initial fossil fuel prices and quantities. This allows us to calculate the consumer surplus loss associated with changes in fuel demand. The regional fuel elasticities are long-run county-level own-price elasticities for gasoline and diesel from Tirkaso and Gren (2020),[10] shown in Fig. 1, panel C and D. For tractability in our mixed-integer model, we construct a stepwise fuel demand function that is divided into five segments (see Appendix D for details). That is, the first 20% reduction can be made at a constant marginal cost, while the following 20–40% reduction incurs a higher constant marginal cost, and so on. The unit costs are calculated as the marginal cost at the midpoint of the segment, using the original linear demand function. We convert fuel volumes to energy equivalents (TJ) using conversion coefficients from the Swedish Energy Agency (2017). For the blend in cap, γ, we consider that technological improvements will increase blend in possibilities. We therefore set the cap well above the minimum required rate suggested by the Swedish Energy Agency (2019b) for 2030. Their suggested rate corresponds to blending in about 38% of ethanol in volume terms,[11] and we assume the cap is 38% in terms of energy content, corresponding to 59% in terms of volume.

Emissions intensities for gasoline and diesel, ε^{gas} and ε^{die}, are obtained from the Swedish Environmental Protection Agency (2021) and consider that the present fossil fuel quantities are blended with some biofuel. Emissions intensities for feedstock production, ε_i^{FEED}, are obtained from Ahlgren et al. (2011). For biofuel production emissions, ε^{OP}, we use data for ethanol made from wheat straw in Europe in Bonomi et al. (2019, p 39), while emissions intensities for transport of feedstock, ε^{TR}, are from Leduc (2009, p.37). Those are also used to calculate the emissions intensities for fuel transport, scaled by the difference in transport costs for feedstock and fuel: $\varepsilon^{DISTR} = \varepsilon^{TR}\frac{\varphi^{FEED}}{\varphi^{FUEL}}$.

For the policy target, E^*, we set the baseline maximum emission target level equal to total emissions from gasoline consumption in 2018, i.e., 6.73 Mt CO_2. This corresponds to a 44% reduction in all emissions from gasoline and diesel.[12]

4.2. Data for biofuel production and distribution

In this section, we provide a brief overview of the data for biofuel production. For further details, see Nordin et al. (2021). With regionally differentiated yield data for reed canary grass, a maximum of 5.8 million tonnes of feedstock can be produced (cf. Figure E1, panel B, in Appendix E). Costs for feedstock are differentiated at the county level and based on the production costs for silage and the opportunity costs for spring barley.[13] Marginal costs increase with the level of feedstock production in each region as land with successively higher opportunity costs is claimed for feedstock production. Marginal costs are calculated using own-price elasticities for forage supply (cf. Figure E1, panel A, in Appendix E).

Feedstock is used to produce biofuel, one tonne of feedstock can be converted to 0.3 m^3 biofuel. Investment and production costs are assumed equal in all regions. The annual production capacities considered are 15–180,000 m^3 biofuel for low capacity facilities and

[9] Biofuels have a VAT of 25%, but are exempt from energy and CO_2 taxes. This is added on the costs for biofuel production, c^{BIO}.

[10] Tirkaso and Gren (2020) estimate country level elasticities based on county-level panel data for 2001 to 2018. Regional elasticities were then calculated based on the country level elasticities, and the relative share of gasoline versus diesel consumption in each county, which is sufficient given homogenous prices across the country and an assumption of symmetry concerning the compensated cross price derivatives. The use of long-run elasticities ensures that the demand functions implicitly capture different options to reducing fuel use, such as changes in transport choices, e.g., to cars with more efficient engines, and a shift to electric vehicles. However, electric vehicles are recently introduced and only present in their data to a limited extent.

[11] The Swedish Energy Agency's (2019c) suggestion of a minimum emissions reduction level for gasoline is 28%, by 2030, equaling about 38% volume blending with biofuels.

[12] Given that we model biofuel that can replace gasoline, hence gasoline emissions are more relevant to compare with than, for example, emissions from all fossil transport fuels.

[13] Opportunity costs are updated in this study to equal Separable costs 4 per hectare in the Agriwise business calculation data base (Agriwise, 2019), in other respects it equals the calculation of costs in Nordin et al. (2021).

180–360,000 m^3 biofuel for high capacity facilities. We assume that the transport of feedstock and biofuel occurs by truck, and costs are based on distances and quantities. Transport distances are measured as the distances between centres of all municipalities in Sweden, multiplied with regional tortuosity factors.

5. Scenarios

To analyse the role of increases in biofuel use and reductions in fuel use in a cost-effective policy for the transport sector, we set up scenarios. In our main set of scenarios, we consider national GHG emissions targets in the road transport sector, ranging from a 10% (*Reduction 10*) to 100% (*Reduction 100*) reduction compared to the maximum emissions decrease of 6.73 Mt CO_2, see Table 1. Thus, the *Reduction 100* scenario implies a reduction in CO_2 emissions equivalent to total gasoline emissions as of 2018. In the *Reduction* scenarios, both biofuel replacement with domestic second-generation biofuel and reductions in fuel end use can be used to abate emissions. These scenarios are used to examine the impact of increasing stringency of emission targets on minimum total costs and the associated cost-effective allocation of measures.

The next set of scenarios, *Reduction No Bio,* ranges over the same absolute levels of emissions reduction, but the targets can only be reached through reductions in fuel end use. By comparing *Reduction No Bio* to the *Reduction* scenarios, we can investigate the cost savings from including domestic second generation biofuel in the portfolio of abatement options.

Next, we examine whether the spatial organisation of biofuel production differs for a given production level, depending on whether we have an emissions reduction target or a production target. This could be the case because biofuel emissions differ spatially for feedstock and transportation, and the blend-in cap restricts biofuel consumption in each region. To this end we construct three additional sets of scenarios. First, we have a set of scenarios with production targets set equal to the total biofuel production levels under the *Reduction* scenarios, denoted *GHG target based production target*. This allows us to study the difference in costs, emissions, and spatial configuration for a given level of biofuel produced under the two different types of targets.

Thereafter, we want to assess the difference in costs for achieving a given emissions reduction under emission and production targets, respectively. We then define two additional sets of scenarios. First, we have *Production target* scenarios, where the biofuel production target level ranges from 10% to 90% of the maximum feedstock quantity in the model (1.7 million m^3). These production targets imply different emissions reductions. In the next set of scenarios, *Production target based GHG target*, emissions reduction targets are set equal to the emissions reduction levels resulting from the *Production target* scenarios.

Table 1
Scenario details.

Scenario set	Target	Abatement options
Reduction	Emissions reduction equivalent to 10–100% of 2018 gasoline emissions (6.73 Mt CO_2).	Biofuel replacement and reduction in fuel end use.
Reduction No Biofuel	Emissions reduction equivalent to 10–100% of 2018 gasoline emissions (6.73 Mt CO_2).	Reduction in fuel end use.
GHG target based production target	Production volume equivalent to the optimal production volume in *Reduction* scenarios.	Biofuel replacement.
Production target	Production volume equivalent to 10–90% of 1,700 t m^3 biofuel.	Biofuel replacement.
Production target based GHG target	Emissions reduction equivalent to GHG emissions reduction in the optimal solution for *Production target* scenarios.	Biofuel replacement and reduction in fuel end use.

6. Results

In sections 6.1 through 6.4, we present and analyse our results in terms of total and marginal costs to reach policy targets, allocation of abatement measures, and land use impacts, at national and regional scale. Lastly, in section 6.5 we present a sensitivity analysis.

6.1. Total and marginal costs at the national level

Fig. 2 shows total costs in the *Reduction* scenarios. As can be seen in the figure, total costs increase at an increasing rate with the stringency of the target. The total costs consist of consumer surplus losses; biofuel costs, including costs for feedstock, feedstock transport, investment, fuel production, and fuel distribution, and the avoided cost for gasoline purchases. Total costs (dark dots) result in a net gain of €23 million in the *Reduction 10* scenario, as biofuel production costs are low at low levels of production. The costs increase to €1704 million in the *Reduction 100* scenario. At lower target levels, costs increase mostly due to increased biofuel production costs (green) but are accompanied by reduced gasoline purchase costs (blue). The share of feedstock costs increases with the reduction target, while feedstock transport costs decrease, reflecting the shorter distances when there are more production facilities. Simultaneously, biofuel distribution costs increase as there is less gasoline available for blending biofuel in each region. For higher target levels, the consumer surplus losses due to decreases in fossil fuel consumption dominate (orange).

Fig. 3 shows the marginal abatement cost (MAC) in € per tonne CO_2 for different scenarios. The blue graph shows the MAC for the *Reduction* scenarios, which increases with target stringency, as biofuel production and fuel reductions become more expensive. Starting off at €0 at a 0.7 Mt CO_2 reduction, where biofuel production implies cost savings, it rapidly increases to €112 at 1.3 Mt, and reaches €642 at 6.7 Mt. After the initial increase, the rate of increase is slower, but then increases again as feedstock production possibilities become more expensive or are even exhausted in some regions, and consumer surplus losses increase with further reductions in fuel end use. The grey graph indicates the replacement value of biofuel, i.e., the cost savings of adding biofuel as an option in the abatement portfolio.[14] It shows that compared to only having the option to decrease fuel use (yellow line), also having biofuel in the abatement portfolio saves costs. The replacement value is initially large, but decreases as reduction of fuel end use and biofuel replacement become approximately equally costly at medium targets. As abatement levels increase, the replacement value increases, since biofuel replacement is less expensive than reductions in fuel use. However, at the highest abatement levels, the blend-in cap restricts blending, reducing the marginal gains of having biofuel as an abatement option.

With a production target, emissions reductions occur as a by-product of biofuel production as biofuel replaces emission-intensive gasoline. At higher production target levels, the MAC[15] is much larger than under an equivalent emission target because the most expensive feedstock is used,[16] while less expensive choices of reduction in fuel end use are employed in the *Reduction* scenarios.

[14] The replacement value is calculated as the difference between the MAC of the Reduction scenarios, and the MAC for the Reduction no bio scenarios, where in the latter case decreased fuel use is the only abatement option.

[15] For production targets, we calculate an approximate value for the MAC by dividing the increment in cost by the decrease in emissions, measured between one production target level and its closest higher target level.

[16] The maximum emissions reduction under the Production targets is constrained by biofuel feedstock availability and equals 1.6 Mt CO_2 in the Production target 90.

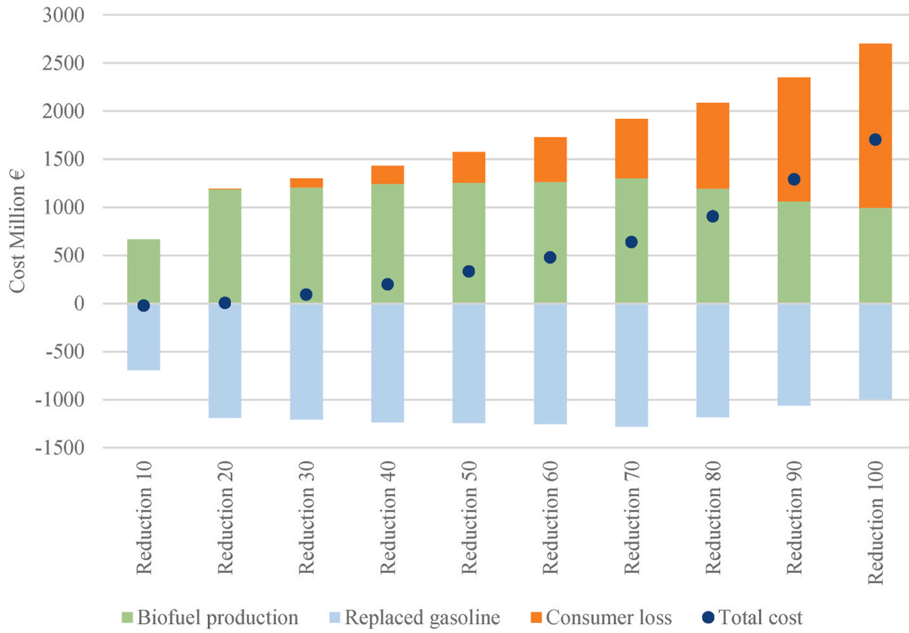

Fig. 2. Total costs (dark dots) in millions of euro required to reach the policy targets in the Reduction 10 to Reduction 100 scenarios. Biofuel production costs (green) less avoided costs for gasoline purchases due to gasoline replacement (blue), and consumer surplus loss from reduced end use of gasoline-biofuel blend and diesel (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

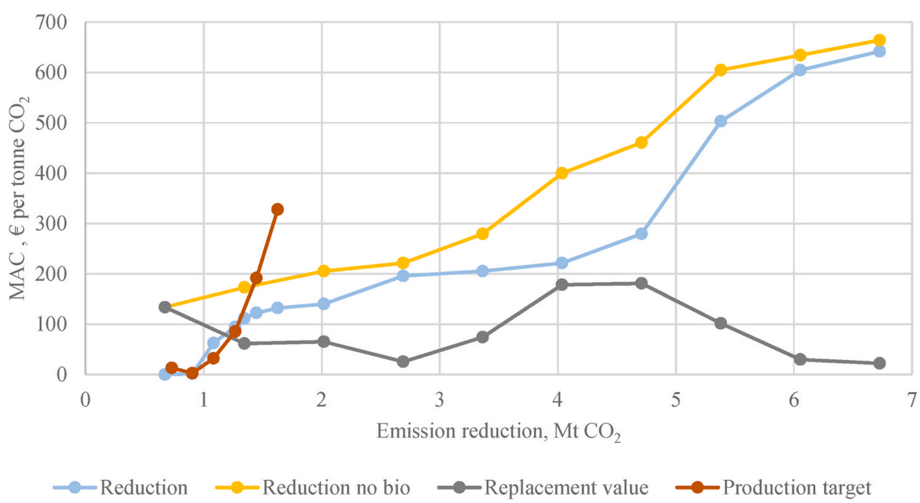

Fig. 3. Marginal abatement cost (MAC) in € per tonne CO_2 at different emissions reduction levels for scenario sets. Blue line: Reduction 10 to 100 and Production target based GHG target 10 to 100. Yellow line: Reduction no bio 10 to 100. Red line: Production target 10 to 100. Grey line: replacement value, i.e., difference in MAC between having biofuel as an abatement option (Reduction) and not having it (Reduction no bio). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

6.2. Allocation of cost-effective abatement measures at a national level

Next, we calculate the cost-effective allocation of emissions reductions across biofuel production, biofuel replacement, and reductions in gasoline and diesel. Fig. 4 shows emissions reductions for each *Reduction* scenario, where the black dots show total net emissions reduction. As was indicated above, replacing gasoline with biofuel (blue bars) is the dominant abatement strategy at lower target levels. Increased emissions from the biofuel supply chain accompany these reductions (green bars), but those are smaller than the reductions from replacement. At higher target levels, the reduction of fuel end use becomes successively more important, first with gasoline emissions reduction (red bars) and later with more diesel emissions reduction (yellow bars). In the most stringent scenario, *Reduction 100*, gasoline emissions are reduced by 64%, and diesel by 28%. At high target levels, the role of biofuel decreases because the cap on biofuel blending is binding, while the use of gasoline decreases implying reduced availability of gasoline for blending the biofuel. Although there is an option to further reduce diesel consumption, this is costly implying that instead gasoline consumption is reduced.

6.3. The spatial distribution of marginal costs for biofuel production

To arrive at the cost-effective implementation of the GHG targets described above (*Reduction 10* to *100*), a carbon tax equal to the marginal abatement cost in Fig. 3 could be introduced, applied to all emissions at their respective sources (cf., e.g., Baumol et al., 1988, pp 21-23). While this is relatively easy to implement for fossil fuels, it could present challenges when addressing emissions associated with biofuels. This is due to the spatial variation in emission intensity of feedstock production,

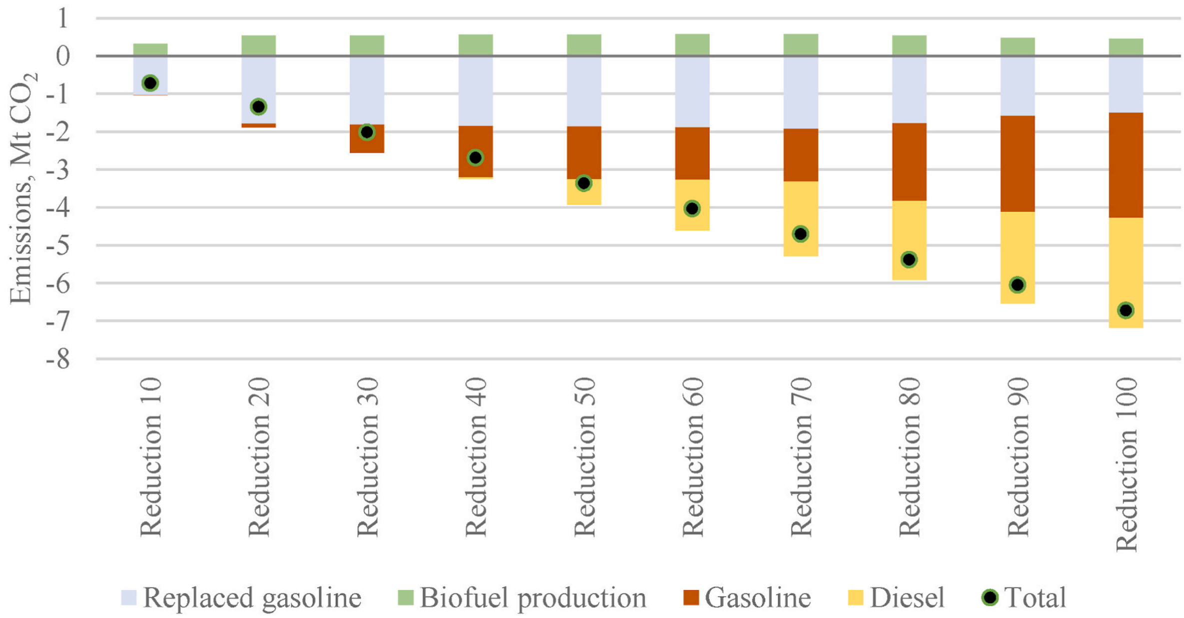

Fig. 4. Total emissions reductions (black dots) and emissions reductions per emission category (bars) in Mt CO_2 for the Reduction 10 to 100 scenarios. "Replaced gasoline" (blue) denotes reduced gasoline emissions due to replacement of gasoline with biofuel, while "gasoline" (red) denotes reduced gasoline emissions due to reduced fuel end use. Yellow bars show the reduction in diesel emissions, and green bars the emissions from the biofuel supply chain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

implying that a spatially differentiated tax would be optimal. The introduction of a CO_2 tax on biofuel production could also be difficult to communicate. Stakeholders might find it counterintuitive to tax an activity that reduce net carbon emissions, and the spatial variation in the tax might be seen as unfair by farmers. An alternative strategy for achieving the cost-effective levels of feedstock and biofuel production in the *Reduction 10* to *100* scenarios could then be to introduce subsidies to feedstock production and biofuel processing, combined with a tax on fuel use. These subsidies and taxes could be set equal to the marginal costs for each measure in each region (Baumol et al., 1988, pp. 36-47). Given the spatial heterogeneity in emissions and costs, there are spatially differentiated marginal costs in optimum and, hence, spatially differentiated subsidies for feedstock and biofuel production. The fuel end use could, simultaneously, be taxed in proportion to its carbon content as is generally suggested by the literature and applied in practical policies.

We calculate the marginal costs for feedstock production and biofuel production capacity in each region to obtain an indication of the variation of cost-efficient subsidies across space.[17] The marginal cost of feedstock production is defined as the highest opportunity cost for land devoted to feedstock production in each region, including the shadow values associated with the land use constraint. The marginal cost of biofuel production capacity is defined as the sum of the unit investment and operations costs, plus the shadow value for high-capacity facilities that meet the capacity constraint.[18] We focus on two scenarios: the *Reduction 70* scenario is equal to the target for the Swedish transport sector to reduce its emissions by 70% by 2030, applied to only gasoline emissions. The *Reduction 40* scenario is just above halfway to that target.

Marginal costs for feedstock in the *Reduction 40* scenario are shown in panel A, Fig. 5, where darker colour indicates higher marginal costs. The marginal costs range from €120 to €210 per tonne feedstock, with the higher levels close to production facilities. This pattern arises as total marginal costs for purchasing and transporting feedstock from a region to a facility should equal the value of the marginal contribution to the emissions target for optimality. The spatial variations in marginal emissions from feedstock production determine the variations in marginal costs from feedstock, together with the marginal costs associated with transportation of feedstock. In regions close to production facilities, feedstock transport costs are low and, hence, the marginal feedstock costs are high in optimum.

For the *Reduction 70* scenario (panel A in Figure E1, Appendix E), the marginal costs are generally higher than for the *Reduction 40* scenario, and to a larger extent determined by shadow values of the land availability constraint, i.e., more than the available feedstock from these regions would be valuable, despite the high costs.

The increased use of feedstock in the whole country at more stringent targets makes it possible to have more high-capacity production facilities. As these have lower marginal costs than the low-capacity facilities,[19] more stringent targets can lead to lower marginal costs, i.e., smaller subsidies are needed when there is a potential for scale economies in production. Panel B in Fig. 5 shows the marginal costs for increased production capacity under *Reduction 40*. The marginal costs range from €140 to €160 per m^3 biofuel for different facilities and are highest for the southeastern facility (dark purple). This is explained by the high marginal investment cost for this relatively small facility. In the *Reduction 70* scenario (panel B in Figure E1, Appendix E), the marginal costs at each facility are almost equal to those in *Reduction 40*, as the facility sizes are similar.

Cost savings would accrue from a technological development that allows for larger blend-in rates, reflected in the shadow value of the

[17] As the OSICPLEX mixed integer programming (MIP) solver does not provide shadow values, we re-ran the model as a linear programming (LP) model to get the same solution including shadow values. To do so, we changed the definition of the binary investment choice variables $I_{v,i}$ to continuous variables but fixed them to their optimal value of 1 or 0 to achieve the same solution as in the MIP formulation. From the LP solution, we got the shadow values of the capacity constraints, feedstock constraints and blend-in constraints. Details on the calculations can be found in Appendix G.

[18] We only present the marginal costs for the regions with a production facility in the optimal solution. The part of marginal costs relating to fixed investments are calculated by dividing the fixed investment cost with the production capacity.

[19] Except in cases when there is a shadow value of the capacity constraint: for two of the facilities in Reduction 40, but for none in Reduction 70.

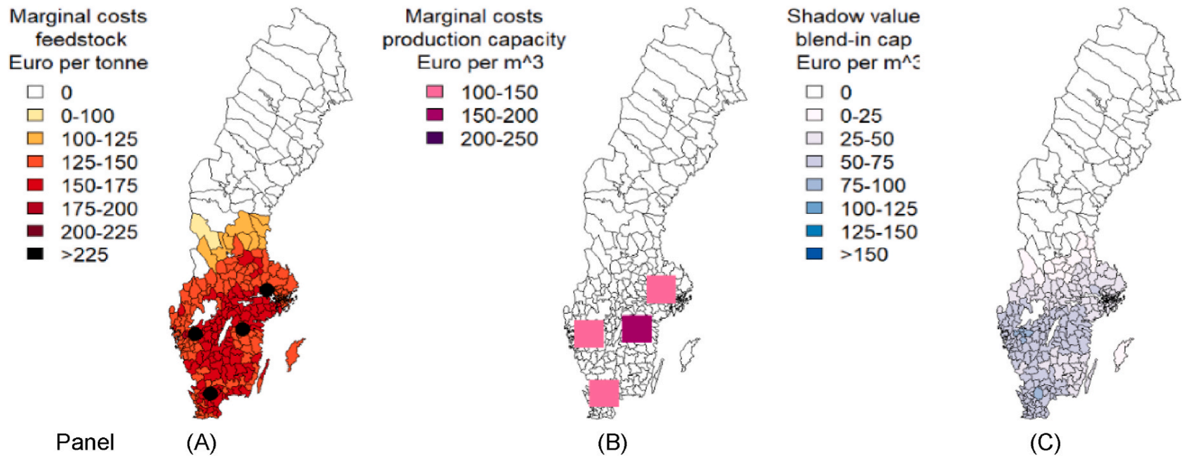

Fig. 5. Marginal costs for the Reduction 40 scenario. Panel A: feedstock production in € per tonne. Panel B: production capacity, € per m^3. Panel C: shadow value of the blend-in cap, € per m^3. Darker colour indicates higher marginal cost. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

blend-in cap constraint, see panel C in Fig. 5 (and panel C in Figure E1 in Appendix E). These shadow values are largest around the production facilities, explained by the lower cost of distributing biofuel to nearby locations, and hence larger value of extending the cap there.

6.4. Land use impacts

Biofuel production is organised spatially in terms of the localization of production facilities, feedstock uptake and fuel distribution. To study the difference in organisation for the same production level, achieved under a production target and under an emissions reduction target, respectively, we compare the *Reduction* scenarios with the *GHG target based production target* scenarios. The result shows that the spatial organisation is similar under the two target types, except for the *Reduction 100* scenario, where the distribution of biofuel affects the localization more under the emission target (see panel A through D compared to panel E through H in Figure E2 in Appendix E).

As the biofuel feedstock production requires agricultural land, in particular land used for ley production, which serves as a vital feed source, there is an impact on animal husbandry. We measure the impact of feedstock production on animal husbandry in terms of the change in hectares of land for ley production per livestock unit (LSU). We simplify this by assuming that all land used for feedstock was previously used for ley production, rather than specifying the smaller part that was used for crop production. The relative impact compared to the case without biofuel is higher in all regions for scenarios with an overall greater level of biofuel production (see Figure E3 in Appendix E for the NUTS1 regions). In eastern Sweden in the *Reduction 70* scenario, the reduction is the highest, equal to 48%, whereas the corresponding reduction is 15% and 41% for the northern and southern part of the country, respectively. In absolute terms, the largest change occurs in southern Sweden.

6.5. Sensitivity analysis

We conduct sensitivity analyses with respect to important model assumptions, listed in Fig. 6, to test the robustness of the model results

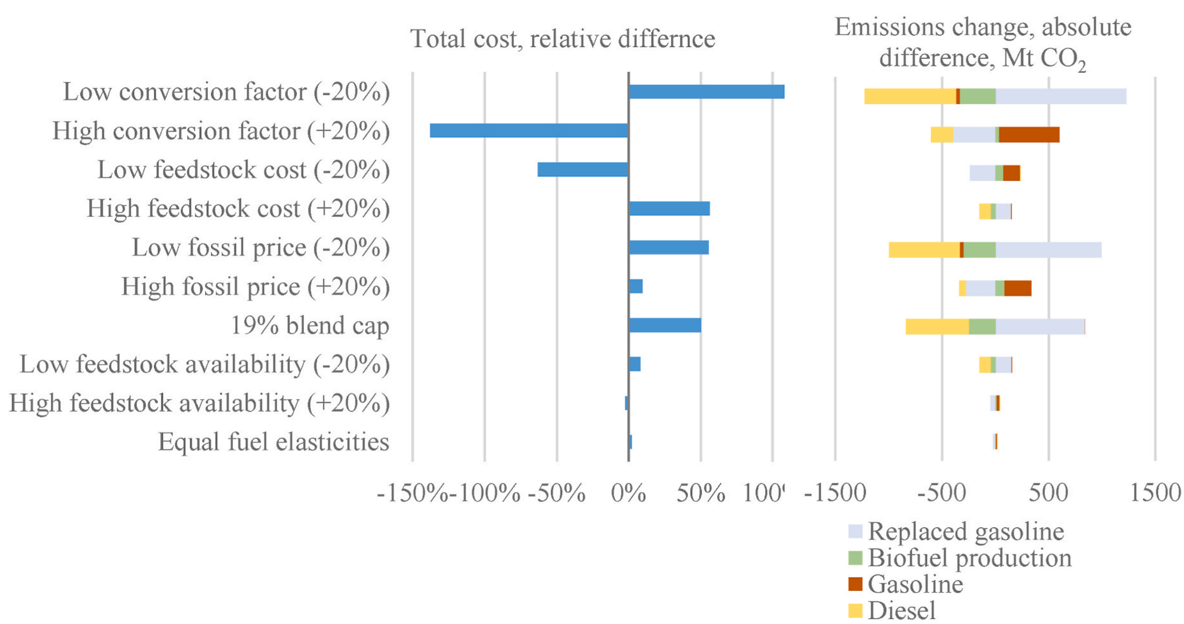

Fig. 6. Sensitivity analysis for the Reduction 40 scenario. Panel A: relative difference in total costs, sensitivity analysis. Panel B: absolute difference in emissions or emissions reduction per source in Mt CO_2. Blue bars indicate changes in emissions reduction from replacing gasoline with biofuel; green indicates change in emissions from the biofuel supply chain; red indicates changes in emissions reduction from decreasing gasoline use; and yellow indicates changes in emissions reduction from decreasing diesel use. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with regard to total cost and the allocation of abatement measures. We focus on the economic and technological parameters of the model, and examine the outcomes under the *Reduction 40* scenario. Panel A in Fig. 6 shows the percentage change in total cost, and Panel B shows the change in emissions in Mt related to different measure. In the figure, parameters are ordered with those causing the largest impact on total costs at the top. Changes in the feedstock conversion factor affects total costs dramatically: a 20% lower factor implies an increase in costs by 129%, and a 20% higher factor implies a decrease by 138%. This is mainly due to the impact on biofuel replacement of gasoline. Next, 20% lower feedstock costs imply 63% lower total costs, associated with increased biofuel replacement. A corresponding increase in feedstock costs has a smaller impact. We note that 20% higher fossil fuel prices[20] lead to 9% higher total costs and a larger share of abatement through biofuel replacement. When fossil fuel prices are lowered by the same proportion, the increase in total costs is 55%. In the first case, the net cost of biofuel is reduced, but the reduction in consumer surplus is larger. In the second case, less biofuel is optimal, and instead diesel is further reduced at high cost. A more restrictive blend-in cap (19%) gives 50% higher total costs and a large decrease in biofuel replacement. Equal fuel elasticities[21] across all regions are implemented in the model to examine the importance of using spatial data on the demand side. The total costs are 1% lower with equal elasticities, with a small increase in biofuel replacement. Changes in feedstock availability gives less than a 2% changes in total costs and a small change in biofuel replacement.

7. Discussion

We found large cost savings from including both reductions in fuel end use and domestic second-generation biofuel production in the carbon abatement portfolio, compared to a policy only focusing on reductions in fuel end use. The marginal abatement cost (MAC) for meeting a carbon emissions target for the transport sector was up to 45% lower per tonne CO_2 when biofuel was included. When both abatement options were available, the MAC was estimated to be €0 per tonne CO_2 for a 0.67 Gt CO_2 emissions reduction target and €642 per tonne CO_2 for a 6.7 Gt CO_2 emissions reduction target. These results can for example be compared to Lee et al. (2023) who find a MAC of about €138 per tonne CO_2 for a mandate to use corn ethanol and second-generation biofuel in the US.

Our sensitivity analysis showed that increased fossil fuel and food prices, with the latter implying higher feedstock prices, have opposing effects on the cost-effective level of biofuel use. Higher fossil fuel prices would favour domestic biofuel production, while higher feedstock costs have the opposite effect. This is currently relevant given the Russian invasion of Ukraine in 2022, which has led to surging fossil fuel prices as well as increased crop prices. The net effect on the cost-effectiveness of domestic biofuel production is thus ambiguous.

The sensitivity analysis also showed that the blend-in cap has a considerable impact on costs under a stringent emissions target. Moreover, an increased availability of more expensive feedstock, e.g., produced on crop land, would not contribute to lower costs, despite the associated reduction in transport costs per unit of feedstock when feedstock supply is increased. The conversion rate of feedstock to biofuel had a large impact on biofuel production and use, showing the value of technological development.

Our study has limitations, including the national perspective without trade, in biofuels which does not account for indirect impacts on land use outside the country borders or on world market prices. As have been shown by, e.g., Rajagopal et al. (2011) and Thompson et al. (2011), a decrease in domestic fossil fuel demand in larger countries can decrease global fossil fuel prices, and thus increase emissions. National biofuel expansion can lead to changes in emissions from global land use, as discussed by Searchinger et al. (2008), and the combined effect of fuel markets and land use changes can be large (Abdul-Aman, 2017). Emissions reduction due to reduced food production can counteract these mechanisms, discussed by e.g., Zilberman et al. (2013), but the magnitude is uncertain, and the impact on food prices could be modest (Popp et al., 2011). Moreover, economy-wide impacts are not estimated, but a rough estimation of the impact is given by the total costs for the highest emissions target as a share of Swedish GDP: 0.3% of GDP.[22]

Other impacts on sustainability, e.g., impacts on biodiversity, are not considered in our study, neither are the distributional effects across different regions and stakeholders (Axsen et al., 2020) that are ultimately determined by the choice of policy instrument. Future research could develop on the approach in this paper by including different biofuel technologies and feedstock, considering also electric vehicles, and losses in fossil fuel vehicle efficiency per fill-up due to the blend in of biofuel (Knoll et al., 2009).

8. Conclusions and policy implications

We developed a spatial cost-minimization model for fuel consumption and biofuel production, empirically applied to Sweden, to study cost-effective GHG abatement choices in the road transport sector. The study contributes to the literature by investigating the interactions of reduced transport fuel use and increased blend-in of biofuel in abating GHG emissions, a topic that is largely overlooked in the earlier literature. With our focus on domestic second-generation biofuel feedstock from the Swedish agricultural sector, we contribute to the knowledge on how such interactions affect policy choices in a country with large spatial heterogeneity in the potential for production of biofuels and in the demand for diesel and gasoline. Insights on the interaction mechanisms between the abatement measures can be generally applied, while quantitative results could be generalizable for regions of similar size, geography and policy, e.g., Finland.

We show that biofuel production can reduce social costs for greenhouse gas emission reduction compared to solely focusing on reducing fuel end use. This applies to a small country restricted to domestic production of second-generation biofuels, where social costs are measured in terms of reduced consumer and producer surplus. This implies that in this case domestically produced biofuel can play an important role in climate policies for the transport sector. However, we found that for higher emissions reduction ambitions, the role of biofuel will be limited, and reductions in fuel end use become more important. Therefore, both abatement measures are needed, and the emissions reduction ambition will guide to what extent biofuel should be supported. A technical blend-in restriction limits the amount of biofuel that can be used in the current vehicle fleet. Therefore, a change in the vehicle fleet to vehicles using pure biofuels or development of the quality of the biofuel would be needed for larger employment of biofuel, implying higher costs. In addition, high feedstock costs due to competition with other agricultural land uses limit production in some regions. This indicates that larger production can have an impact on the agricultural sector, in terms of production, prices and GHG emissions.

As could be expected, an emissions target proved a less expensive way to reduce emissions than a biofuel production target in this case study, where only domestic feedstock and biofuel could be used.[23] This

[20] The change in fossil fuel price is modelled as sensitive to the data on the price: we model it as a lower/higher baseline fossil price, while the demand elasticities are the same as before. This implies a shift and tilt of the demand curve. In addition, the reduction in fossil fuel costs as biofuel replaces gasoline is lower/higher per unit.

[21] These are the national level elasticities that Tirkaso and Gren (2020) use to construct the regional elasticities used in this paper.

[22] Swedish GDP as of 2022 from Statistics Sweden (2024), and currency conversion for 2022 (Sveriges Riksbank, 2024).

[23] Or equivalently a target of use of domestic biofuel.

was true in particular at higher production target levels: the marginal abatement cost of the production target was up to 250% higher than the marginal abatement cost for an emissions reduction target reaching the same total emissions reduction. This is because in the former case, the most expensive feedstock had to be used to produce enough biofuel. However, somewhat unexpectedly, we found that when the optimal biofuel production level is known, a production-based target can lead to a cost-effective spatial organisation of biofuel, because spatial variations in biofuel production related emissions have a minor impact on the cost-effective spatial allocation of production.

While fuel use could be targeted with carbon taxation, implementation of a carbon tax on feedstock and biofuel production related emissions could be more difficult. Instead, a policy could be designed where producers of feedstock and biofuel are compensated for their production costs, accompanied with carbon taxation on fuel end use. The compensation could be designed as a subsidy, set at the level of marginal cost for a cost-effective solution. For feedstock production, results show that the marginal costs are the highest close to the production facilities. A larger production of feedstock close to these facilities would thus be valuable despite high feedstock production costs, because it reduces emissions from transports and saves on transport costs. There are also high marginal costs for production and investment in biofuel facilities at optimal locations.

The High-Level Commission on Carbon Prices (2017) concluded that a carbon price of €43–€85 per tonne CO_2 is needed by 2030 to reach the Paris Agreement temperature target. As our marginal abatement costs are comparable at low abatement levels, suggests that it might not be cost-effective for the transport sector to take on a large share of total abatement for more stringent targets. However, the marginal abatement costs that we find are lower than for some Swedish policy measures for transport fuel substitution (NIER, 2007), and should therefore be preferred, when we consider domestic biofuel production in a small country, as in this case study.

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CRediT authorship contribution statement

Ida Nordin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Katarina Elofsson:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Torbjörn Jansson:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT3.5 in order to improve grammar and spelling in the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

model code and data available at github repository (see reaserach data in Attach file step

biofuel_model (Original data) (Github)

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Appendix A. Nomenclature

Sets

g	Set of feedstock production regions
i	Set of biofuel production regions
h	Set of end-use regions
s	Set of fuel change cost categories
f	Set of feedstock cost categories
v	Set of facility types
k	Set of fuel for end use
l	Set of pure fuels

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
$x_{i,g}^{TR}$	Feedstock flow between regions Tonne
$x_{f,i,g}^{TR}$	Feedstock flow between regions, per cost category Tonne
x_g	Feedstock Tonne
$x_{f,g}$	Feedstock, per cost category Tonne

$y_{l,h}$	Pure fuel use m^3
$z_{k,h}$	Fuel end use m^3
$z_{s,k,h}$	Fuel end use per cost segment m^3
Y	Total biofuel production Tonne
c^{BIO}	Total biofuel production cost €
$c_{i,v}^{INV}$	Investment cost €
c_i^{OP}	Production cost €
c_i^{FEED}	Feedstock cost €
$c_{i,g}^{TR}$	Feedstock transport cost €
$c_{i,h}^{DISTR}$	Biofuel distribution cost €
c_h^{FUEL}	Cost for fuel use change €
$e_{i,g}^{FEED}$	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_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

$\overline{x}_g$	Available feedstock Tonne
$\overline{x}_{f,g}$	Available feedstock per cost category Tonne
$y_{,hl}^0$	Initial level of fuel m^3
p_l^0	Initial fuel price €/m^3
γ	Maximum share biofuel in blended fuel
$d_{g,i}$	Distance between regionskm
τ_k	Fuel –energy conversion coefficient TJ/m^3
$c_{s,k,h}^{FUEL}$	Costs for changing fuel use €/m^3
$\vartheta_{f,g}$	Feedstock cost €/tonne
ε_{die}	Emission intensity for diesel Tonne CO_2/m^3
ε_{die}	Emission intensity for gasoline Tonne CO_2/m^3
ε^{OP}	Emission intensity for production Tonne CO_2/m^3
ε_i^{FEED}	Emission intensity for feedstock Tonne CO_2/tonne feedstock
ε^{TR}	Emission intensity for transport of feedstock Tonne CO_2/tonne•km feedstock
ε^{DISTR}	Emission intensity for distribution of biofuel Tonne CO_2/ m^3•km biofuel
Y^*	Biofuel production targetp m^3
E^*	Emissions reduction target Tonne CO_2

Appendix B. Stepwise constant demand function

The downward sloping demand function $D^{k,h}$ is approximated stepwise constant with Equation B.2. Total fuel use is divided into segments s, with *s = 1,2, …,S (Equation B.1)*. Each segment s has a constant cost, $c_{s,k,h}^{CONS}$, increasing in s, (Equation B.3).

$$z_{k,h} = \sum_s z_{s,k,h} \ . \tag{B.1}$$

We assume the demand function is constant for each cost segment:

$$D^{k,h} = c^{CONS}\left(z_{s,k,h}\right) = c_{s,k,h}^{CONS} \tag{B.2}$$

$$c_{s,k,h}^{CONS} < c_{t,k,h}^{CONS}, s < t \tag{B.3}$$

Appendix C. Biofuel localization model – equations

$$x_g = \sum_f x_{f,g} \tag{C.1}$$

$$\overline{x}_g = \sum_f \overline{x}_{f,g} \tag{C.2}$$

$$x_{i,g}^{TR} = \sum_f x_{f,i,g}^{TR} \tag{C.3}$$

$$x_{f,g} \le \overline{x}_{f,g} \tag{C.4}$$

$$x_{f,g} = \sum_i x_{f,i,g}^{TR} \tag{C.5}$$

$$y_i = \alpha \sum_g \sum_f x_{f,i,g}^{TR}, \tag{C.6}$$

$$\underline{y}_v \cdot I_{v,i} \le y_{v,i} \le \overline{y}_v \cdot I_{v,i}, \underline{y}_H = \overline{y}_L \tag{C.7}$$

$$\sum_v I_{v,i} \le 1 \tag{C.8}$$

$$Y = \sum_i y_i \tag{C.9}$$

$$\sum_h y_{i,h}^{DISTR} = y_i \tag{C.10}$$

$$c_{i,v}^{INV} = \rho_v \cdot y_i \cdot I_{v,i} + \delta_v \, I_{v,i} \tag{C.11}$$

$$c_i^{OP} = \sigma \cdot y_i \tag{C.12}$$

$$c_i^{FEED} = \sum_g \sum_f \vartheta_{f,g} x_{f,i,g}^{TR}, \vartheta_{f,g} increasing \; in \, f \tag{C.13}$$

$$c_i^{TR} = \sum_g \sum_f \left(\omega^{FEED} + \varphi^{FEED} d_{g,i} \right) x_{f,i,g}^{TR} \tag{C.14}$$

$$c_i^{DISTR} = \sum_h \left(\omega^{FUEL} + \varphi^{FUEL} d_{h,i} \right) y_{i,h}^{DISTR} \tag{C.15}$$

$$c^{BIO} = \sum_i \sum_v \left(c_{i,v}^{INV} + c_i^{OP} + c_i^{FEED} \right) + \sum_i c_i^{TR} + \sum_i c_i^{DISTR} \tag{C.16}$$

Appendix D. Additional data visualisation

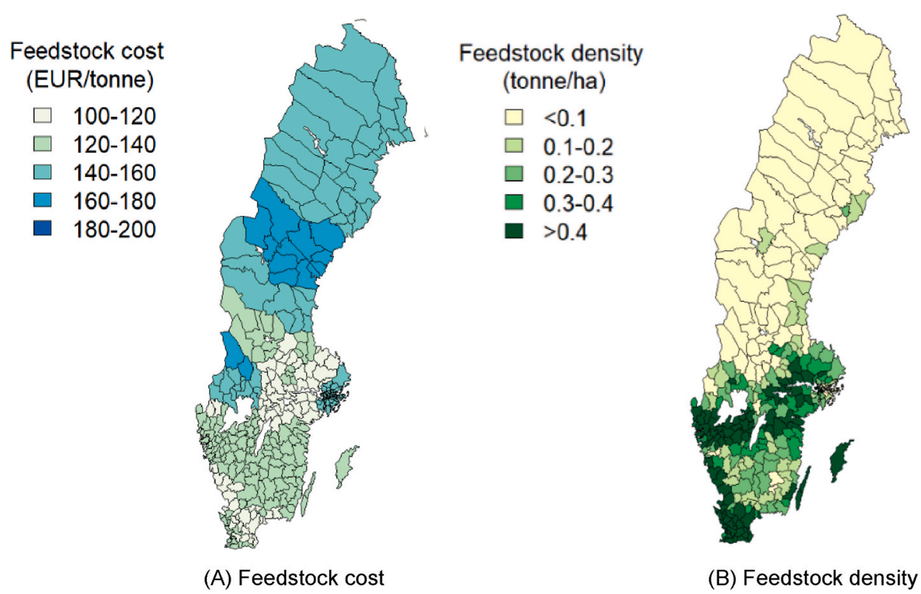

Fig. D.1. Background data. Panel A: feedstock costs in € per tonne for first unit of feedstock. Panel B: Potential feedstock density in tonnes per hectares, based on model assumptions on available land.

Appendix E. Additional results

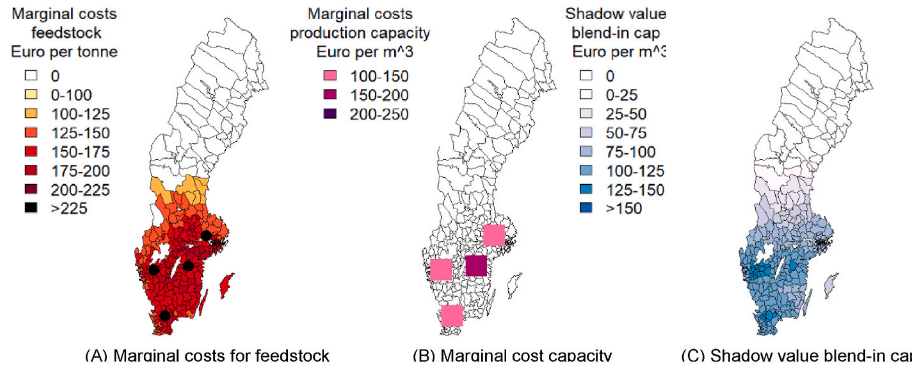

Fig. E.1. Marginal costs for the Reduction 70 scenario. Panel A: feedstock production in € per tonne. Panel B: production facilities, € per m^3. Panel C: shadow value of the blend-in cap, € per m^3. Dark colour indicates higher marginal cost.

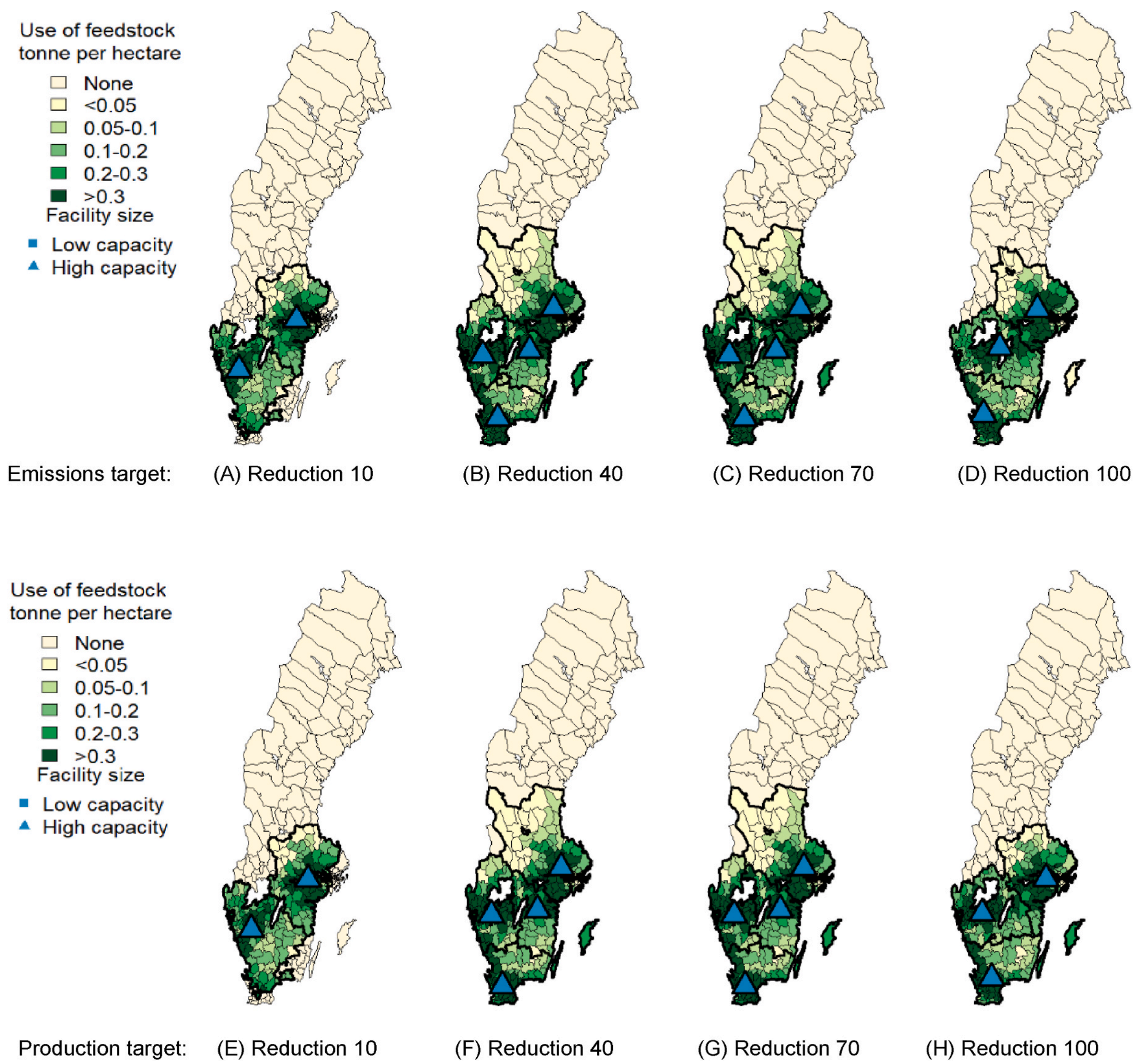

Fig. E.2. Organisation of biofuel production. Emissions target scenarios shown in Panel A, B, C and D, for Reduction 10, 40, 70, and 100, respectively. GHG target-based production target shown in Panel E, F, G, and H, for production targets equalling production levels Reduction 10, 40, 70, 10, respectively. Triangles show facilities with high capacity and squares low capacity. Green areas surrounded by black borders denote areas with supply to a facility. Darker green indicates larger uptake of feedstock.

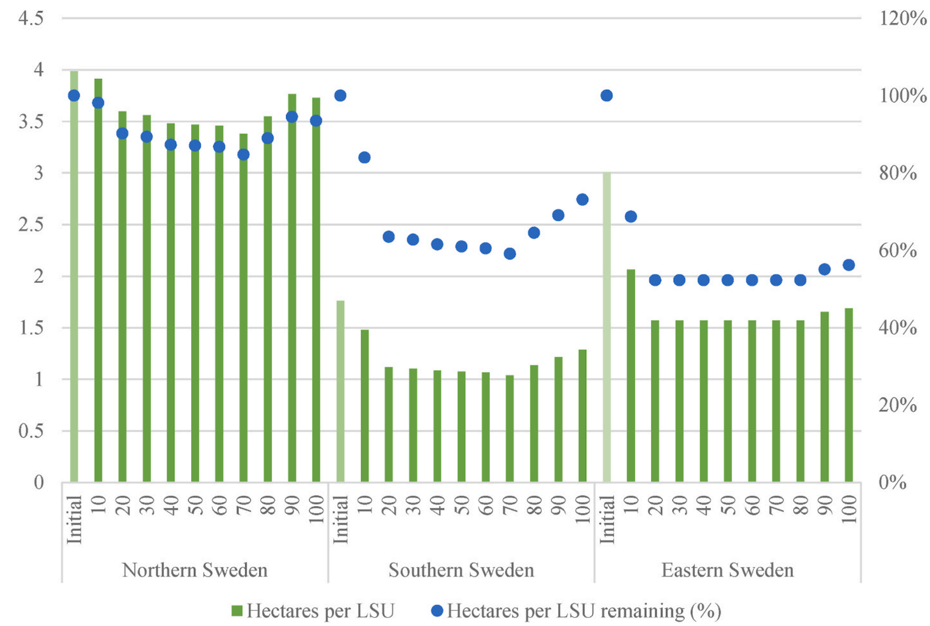

Fig. E.3. Hectares of arable land per livestock unit (LSU) for initial levels, and for the Reduction scenarios, for different regions. Green bars show absolute levels, and blue dots show relative levels as share of initial levels.

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