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Costs and equity of uncertain greenhouse gas reductions – fuel, food and negative emissions in Sweden

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ABSTRACT

Reducing emissions of greenhouse gases (GHG) by reduction of fuel and food consumption and by implementation of negative emissions (such as forest carbon sequestration and carbon capture and storage) has been suggested in both scientific literature and practice, but there exist no calculations of the cost efficient combination of these measures. One challenge for calculations is the uncertainty in reductions of GHG, in particular for negative emissions, depending on e.g. stochastic weather conditions. This paper develops a static model with probabilistic emission constraints to calculate cost efficient emission reductions in the transportation (gasoline and diesel) and food (meat and dairy products) sectors combined with negative emission (carbon sequestration and carbon capture and storage technologies) creation in Sweden under uncertainty. The results show that emission reductions in fuel and food consumption are relatively expensive, and that carbon sequestration are relatively low cost measures. We also show that the regional effects at the county level are regressive, that is, that relatively poor counties will carry large cost burdens in the cost efficient solutions and that this effect is increased when negative emissions are included but decreased when uncertainty is considered.

1. Introduction

Greenhouse gas emissions from transportation and food consumption together account for approximately 1/3 of the global emissions, where transportation accounts for 14% (EPA (United States Environmental Protection Agency), 2020) and consumption of animal products can correspond to 18% (e.g. Clune et al., 2017). A large body of literature in economics is devoted to the calculation of costs and design of policies for reducing emissions from the transportation sector (e.g. Sterner, 2012; Sterner and Coria, 2012; Eliasson et al., 2018; Gillingham and Stock, 2018). Fewer assessments have been made about costs and policy design for reducing the emissions due to consumption of meat and dairy products (e.g. UNEP, 2009; Säll and Gren, 2015; Gren et al., 2021). Price elasticities in both fuel and food demand are low in absolute terms, which implies that large price increases would be needed to obtain significant emissions reductions, and the costs of GHG reductions would then be high. The creation of negative emissions, i.e. reduction of the concentration of carbon dioxide in the atmosphere, has been suggested and implemented in practice as a means of reducing cost and increasing the speed of decreasing the amount of carbon in the atmosphere (e.g. IPCC, 2019; PRI (Principles for Responsible Investment), 2020). In principle, negative emissions can be done by nature based measures such as increasing carbon sequestration in forests and arable land (e.g. Sedjo et al., 1995; van Kooten et al., 2009; Raihan et al., 2019), and through human-made technologies, which include various carbon capture methods (e.g. van Vuuren et al., 2013; Johnsson et al., 2020).

However, most of the measures are associated with an uncertain impact on GHG emission from a change in e.g. food consumption or land use. A decrease in beef consumption affects GHG production by reducing methane emitted by the animals and nitrous oxides and carbon dioxide from land use, but the impact on land emissions are uncertain because they are dependent on weather conditions (e.g. Sykes et al., 2019). For similar reasons, enhancing carbon sequestration through forest management or afforestation is uncertain (e.g. Gren et al., 2012). Negative emissions in terms of CCS and bio-CCS are uncertain because of upcoming developments in the relatively new technologies for carbon capture, transport, and storage (e.g. Leeson et al., 2017; van der Spek et al., 2020). In a risk averse society, such uncertainty is costly and a unit GHG emission reduction from these measures should not be equated with a unit emission reduction from fossil fuel combustion.

Public acceptance of policy is a prerequisite for successful implementation and enforcement of any environmental programs (e.g.

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Kallbekken and Saelen, 2011). Equity in cost burdens of the environmental improvements is one factor that can be used to promote public acceptance, in addition to the perceived legitimacy of the environmental program (Kallbekken and Saelen, 2011; Bachus et al., 2019). A few studies have considered distributional effects of emission reductions from transports (Sterner and Coria, 2012; Eliasson et al., 2018; Tirkaso and Gren, 2020), from food consumption (e.g. Säll, 2018), and from carbon sequestration (Munnich Vass et al., 2013).

The purpose of this study is to calculate a cost efficient combination of reductions in fuel and food consumption, and creation of negative GHG emissions and distributional effects when the impact on emissions is uncertain. To this end, we apply a safety-first decision framework, which has a long tradition in economics (e.g. Tesler, 1955). Emission targets are then formulated as probabilistic constraints where a certain emission reduction is to be achieved at minimum cost with a minimum probability level. Equity is measured in terms of progressive or regressive allocation of costs among counties in relation to their prosperity. The study is applied to Sweden.

There is a large body of literature about calculating costs for reductions in fuel consumption and negative emissions (e.g. Gren et al., 2012; van Kooten et al., 2009), but there are few studies on the costs of reducing GHG emissions under uncertainty (e.g. Gren et al., 2012) and from changes in food consumption. Similarly, despite the well-established literature about price elasticity of fuel (see reviews in Dahl, 2012 and Aklilu, 2020) and derivation of marginal costs for different abatement measures (e.g. Gillingham and Stock, 2018), there are very few studies that estimate minimum cost and equity implication of emission reduction from this sector (Sterner, 2012; Eliasson et al., 2018; Gren and Tirkaso, 2020).

In the authors' view, the novel contribution of the study is threefold; *i)* calculations of cost efficient allocation of abatement in the three classes of abatement measures, i.e. reduction in consumption of transport fuels and food, and introduction of negative emissions, *ii)* consideration of uncertainty in abatement of the measures, and *iii)* calculations of distributional effects of the cost efficient outcomes. The application to Sweden adds to the few studies on cost calculations applied to this country. However, this study makes a simplification by using the marginal abatement cost approach, in which costs are calculated only for the direct impact of the emission reduction, such as the cost of reducing beef consumption, or of increasing carbon sequestration from the land use change. Unlike much of the literature on the costs of climate change mitigation, we do not consider the impacts on the rest of the economy and the associated responses (see Babatunde et al., 2017 for a review). This relatively simple approach has been used in several studies calculating costs of GHG emission reduction (e.g. Gren et al., 2012; Sotiriou et al., 2019). In this study, the advantage of simplicity is that it allows for considering uncertainty within a safety-first decision framework.

The study is organized as follows. The theoretical model is presented in Section 2, data retrieval is described in Section 3. Results and sensitivity analyses are presented in Section 4. The study ends with a discussion and conclusions.

2. Conceptual approach

The analysis includes two main parts: *i)* calculations of cost efficient allocations of fuel and food emission reductions and negative emissions among different counties in Sweden, and *ii)* assessment of equity outcomes in the cost efficient solutions. Cost efficient solutions within the safety-first decision framework are calculated using chance-constrained programming where costs are minimized for the uncertain achievement of an emission target, which is formulated as a probabilistic constraint (e.g. Taha, 1976; McCarl, 2010; Gren et al., 2012). Equity outcomes are measured by means of the Suits index, which is much used for this purpose in the literature (e.g. Sterner, 2012; Eliasson et al., 2018).

2.1. A model of cost efficient emission reduction

A static cost minimizing model is constructed for emission reductions with the three classes of abatement measures in each county i in Sweden. Following Eliasson et al. (2018) and Tirkaso and Gren (2020), the abatement in the transport sector, A^{it}, includes reductions in the use of gasoline and diesel. For food items, it was demonstrated by Gren et al. (2021) that almost 90% of its GHG emissions originated from the consumption of beef, pork, cheese, cream, and other milk products. Reductions in consumption of these food products, A^{if}, are therefore included in this study.

With respect to negative emissions, there are in principle two options; enhancement of nature based carbon sequestration and installation of carbon capture and storage. Starting with Sedjo and Solomon (1989), there is now a large body of literature estimating costs for nature based negative emissions. The rapid development of this literature has resulted in several reviews about calculating carbon sequestration costs (e.g. Sedjo et al., 1995; Manley et al., 2005; van Kooten et al., 2009; Phan et al., 2014). Achieving negative emissions through CCS solutions, which includes capture of emissions from fossil fuels and bioenergy in this study, is widely recognized as an effective mechanism for meeting climate change targets (e.g. Lilliestam et al., 2012; Bergstrom and Ty, 2017; Johnsson et al., 2020). In the present study, we consider negative emissions by measures, A^{ik}, for which cost estimates can be obtained for Swedish counties, which include forest management by delayed harvesting of trees, afforestation, restoration of drained peatland, and construction of CCS.

A cost function is associated with each measure and county, $C^{it}(A^{it})$, $C^{if}(A^{if})$, and $C^{ik}(A^{ik})$. For food and fuel, these costs are associated with welfare decreases from reduced consumption of the goods. Reduced profits from delayed harvesting of trees constitute costs of forest management, and opportunity costs of land occur for afforestation and restoration of drained peatlands. The creation of CCS generates investment and management costs for carbon capture, transport and storage.

The static model necessitates an introduction of constraints on abatement capacities of each measure in the short run perspective. For instance, there are minimum requirements of fossil fuel and food use, and maximum land areas suitable for forest carbon sequestration, and these constraints are written as:

$$A^{it} \leq \overline{A}^{it}, A^{if} \leq \overline{A}^{if}\ A^{ik} \leq \overline{A}^{ik} \tag{1}$$

The probabilistic emission target is imposed on total emissions G, which include uncertain emissions and abatements from each of the three classes of abatement measures according to:

$$G = \sum_i \left(\sum_t G^{it} + \sum_f G^{if} - \sum_k A^{ik} \right) \tag{2}$$

where $G^{it} = G^{it'} - A^{it}$ and $G^{if} = G^{ig'} - A^{if}$. $G^{it'}$ and $G^{if'}$ are emissions from the fuel and food sectors, respectively, under business as usual (BAU) without abatement. Emissions from the fuel and food sectors, G^{it} and G^{if}, are both uncertain, and have means μ^{it} and μ^{if} and variances σ^{it} and σ^{if}. Similarly, negative emissions are uncertain with mean μ^{ik} and variance σ^{ik}.

Uncertainty in abatement by the measures implies uncertainty in obtainment of a given emission target $\overline{G}$. This is accounted for by applying the chance-constrained optimization method, which implies that a decision-maker has to decide the minimum probability, α, at which the emission target, $\overline{G}$, should be achieved (e.g. Taha, 1976; McCarl, 2010). The probabilistic emission target is written as:

$$prob\left(G \leq \overline{G}\right) \geq \alpha \tag{3}$$

Given the abatement cost functions, abatement capacities, and the target emission target the safety-first decision problem is written as:

$$\underset{A^{it}, A^{if}, A^{ik}}{Min} \quad C = \sum_i \left(\sum_t C^{it}\left(A^{it}\right) + \sum_f C^{if}\left(A^{if}\right) + \sum_k C^{ik}\left(A^{ik}\right) \right) \tag{4}$$

s.t. eqs. (1), (3).

In order to solve the optimization problem, there is a need to transform the probabilistic emission target in eq. (3) to a deterministic equivalent (e.g. Taha, 1976; McCarl, 2010). As shown in Appendix A, the probabilistic constraint in eq. (3) can be written as:

$$\mu + \phi^{\alpha}(\sigma)^{1/2} \leq \overline{G} \tag{5}$$

where $\mu = E[G]$ is the mean emission, $\sigma = Var(G)$ is the variance in total emission, and the term ϕ^{α} is the number of standard errors at the chosen probability α.

Eq. (5) shows that the emission target restriction becomes tighter because of the risk discount shown by the second term $\phi^{\alpha}(\sigma)^{1/2}$ to the left of the inequality sign. This means that more abatement is needed to ensure target achievement, which raises the total abatement costs. We denote this extra abatement as a safety margin, which is defined as $\phi^{\alpha}(\sigma)^{1/2}$. The parameter ϕ^{α} in the safety margin reflects the decision-maker's risk aversion to non-attainments of the abatement targets: when $\phi^{\alpha} > 0$, the decision maker is concerned about reaching the targets, and when $\phi^{\alpha} = 0$, the decision maker is not concerned about reaching the target.

The level of ϕ^{α} is determined by the choice of probability of reaching the target, α, and the probability distribution. Because there is no empirical evidence, there are no a priori expectations about the probability distributions. In this study, we apply the common approach to assume a normal probability, and ϕ^{α} is then determined by $\int_{-\infty}^{\phi^{\alpha}} f(\phi^{\alpha})d\phi^{\alpha} = \alpha$, the calculation of which can be found in students' t-tables where, for example, $\phi^{\alpha} = 1.28$ (one tail) when $\alpha = 0.9$ (see e.g. Taha, 1976).

As detailed in Appendix A, a cost efficient solution requires that marginal abatement costs are equal for all measures, which is written as:

$$\frac{\partial C^{it}}{\partial A^{it}} - \lambda^{it} \Bigg/ \frac{\partial \mu}{\partial A^{it}} - \frac{\theta^{\alpha}}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{it}} = \frac{\partial C^{if}}{\partial A^{if}} - \lambda^{if} \Bigg/ \frac{\partial \mu}{\partial A^{if}} - \frac{\theta^{\alpha}}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{if}} = \frac{\partial C^{ik}}{\partial A^{ik}} - \lambda^{ik} \Bigg/ \frac{\partial \mu}{\partial A^{ik}} - \frac{\theta^{\alpha}}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{ik}} = \lambda \tag{6}$$

where $\lambda < 0$ is the Lagrange multiplier which shows the change in total cost for a marginal change in $\overline{G}$, and λ^{it}, λ^{if}, and λ^{ik} are the Lagrange multipliers of the capacity constraints of the abatement measures. The numerator of each expression shows the marginal cost at source and the denominator shows the impact on the target. For all measures, the impact consists of two parts: the effect on average emissions, which is negative, and the effect on the variability, which is positive. A high marginal impact on the mean emissions and low impact on the variance, implies a cost advantage. Measures with a relatively high impact on the variance then have cost disadvantages.

2.2. Distributional effects

For each cost efficient solution, equity outcome between counties is measured in terms of progressivity or regressivity. A progressive (regressive) outcome implies that the cost burden of relatively poor regions is low(high) compared to the cost burden of relatively rich counties. In this paper, these two descriptors are measured by the Suits index (Suits, 1977), which shows the magnitude of progressivity and regressivity in the allocation of costs.

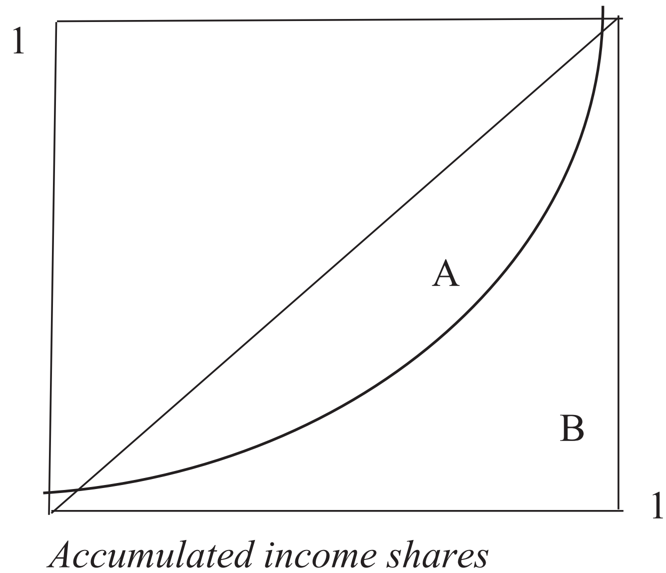

Fig. 1. Illustration of Lorenz curves for perfect and imperfect equity with respect to allocation of abatement cost in relation to income.

The calculation of the Suits index is based on the Lorenz curves, which relate the accumulated abatement cost shares to income shares for the counties. Two functional forms are illustrated in Fig. 1 where the Y-axis shows accumulated shares of increasing costs. The X-axis is the accumulated income shares. The linear Lorenz curve in Fig. 1 shows a neutral allocation of costs since the share of the cost burden is the same as the share of total income at all levels. The nonlinear curve illustrates a progressive allocation where a certain income share pays a lower share of the total cost.

The Suits index, *I,* is calculated as the ratio between the *area A* in relation to the area with a neutral allocation of costs, i.e. the area under the line that corresponds to *area A* + *area B* = *0.5*, which gives *I* = *area A/0.5*. Noting that *area A* = *0.5* - *area B* and that *area B* can be calculated as the sum of trapezoid areas, the index is calculated as:

$$I = \frac{0.5 - \sum_i 0.5\left(S^{C^i} + S^{C^{i-1}}\right)s^{Y^i}}{0.5} = 1 - \sum_i \left(S^{C^i} + S^{C^{i-1}}\right)s^{Y^i} \tag{7}$$

where $S^{Ci} = \sum_{j \leq i} s^{Cj}$ is the accumulated cost shares of the counties, $s^{Ci} = C^i / \sum_i C^i$, sorted in ascending order where $C^i > C^{i-1}$, and s^{Yi} is the share of income for a county defined as $s^{Yi} = Y^i / \sum_i Y^i$. The distributional allocation of costs is progressive when $I > 0$ and regressive when $I < 0$, since *area A* in Fig. 1 is relatively small and large, respectively. By calculating *I*, information is also obtained about the magnitude of the effects, which is useful when comparing distributional outcomes under different scenarios (Section 4).

A common result from studies calculating distributional effects of carbon policies is that the choice of a reference point of the cost, i.e. Y^i, can affect the outcome (see meta analysis by Ohlendorf et al., 2021). A common practice is to consider economic instruments, in particular on fuel, and relate the cost to disposable income. Similar to present study, the cost is calculated as changes in consumer surplus, which include increase in costs for actual fuel use and welfare loss from reductions in fuel use. The present study includes only the welfare loss from reductions in consumption of fuel and food where charges/subsidies are regarded as transfer and not as a social cost although it is a real cost for the individuals. Therefore, costs for a county are related to the gross regional product (GRP), which reflects the annual market income of a region.

3. Description of data

The numerical solution to the model described in Section 2 requires data about abatement capacity, uncertainty quantification and costs of different abatement measures, probabilistic constraints, and income measurements for each county. There are 21 counties in Sweden (Fig. B1), which differ with respect to emissions from fuel and food and availability of negative emissions. The calculations are made for year 2018, and unless otherwise stated, all data is found in Gren and Tirkaso (2020).

3.1. Abatement potential and uncertainty quantification

Emissions from fuel and food are calculated by assigning constant emission per unit of consumption good. Negative emissions from afforestation and restoration of drained peatlands are calculated based on constant emissions per unit of land area. Given the static model, maximum emission reductions from reducing fuel and food and increasing negative emissions are limited by consumption constraints and development of measures for carbon sequestration and CCS. With respect to fuel and food emission reductions, it is simply assumed that the consumption level of each good can be reduced by a maximum of 60% of the consumption of each good in 2018. The total emission from fuel amounts to 19.1 million metric tonnes, and from food, 8.2 million tonnes, which gives a total of 27.3 million tonnes. The maximum emission reductions then amount to 11.5 t and 4.9 t carbon dioxide equivalents (CO_2e) for fuel and food respectively, see Table 1 for more details.

With respect to the maximum capacity of carbon sequestration from forest management, Guo and Gong (2017) reported an average annual maximum carbon sink enhancement of 6 million tonnes CO_2e. It is assumed that 33% of this sequestration can be implemented in the short run. Regarding afforestation, it is assumed that forests are planted only on impediment arable land, which is defined as agricultural land not managed in the last five years, and that half of the impediment and drained peatlands can be used for afforestation and restoration. With respect to CCS removal capacity, Johnsson et al. (2020) calculated a potential carbon capture at facilities in Sweden which amounts to 23 million tonnes. Since this can be implemented only in the long run, it is simply assumed that a fraction, 15%, of the potential can be captured and stored and this carbon capture will be proportionally allocated among counties according to their emissions from industry and energy production (SEPA (Swedish Environment Protection Agency), 2020). The assumed total capacity of negative emissions then amounts to 8.2 million tonnes CO_2e of which 4.75 million tonnes are obtained from carbon sequestration and 3.45 million tonnes from CCS (Table 1).

For all measures, uncertainty in abatement is measured by the coefficient of variation (CV), which shows the ratio between the standard deviation and the mean. Such data are not available at the county level, and each CV is therefore assumed to be the same for all counties. The CVs for gasoline and diesel are obtained from Gren et al. (2012). Emissions from food items usually include a life cycle perspective, which considers emissions from transports of the food from producers to consumers (e.g. Säll and Gren, 2015). The inclusion of all emissions would therefore imply double counting the emissions from transports. For this reason, we only consider the emissions from the production of the food, which mainly includes methane and nitrous oxides. Emissions of methane are relatively certain since these depend almost entirely on livestock enteric fermentation, and livestock can be counted. Emissions from land, on the other hand, in terms of nitrous oxides and carbon dioxide, depend on the (stochastic) weather conditions and so are less certain. Sykes et al. (2019) calculated means and standard deviations for beef, and the corresponding coefficient of variation in emission factors vary among methane, nitrous oxides, and carbon dioxide from 0.1 and 0.6, with the lowest for enteric fermentation and highest for N_2O from fertilizers from soil. The overall CV amounted to 0.13, which is used in this paper. Because of lack of data, this CV is assigned to all included food items.

The problem of uncertainty in carbon sequestration is well-known, but there are few quantifications of standard deviations and means of different carbon sequestration options. For Sweden, there are estimates of carbon sequestration from forests (Gren and Carlsson, 2013), and the coefficients of variation for forest management and afforestation are assumed to be the same. Gren and Tirkaso (2020) calculated standard deviations of restoration of peatlands. CCS technology is still in the pilot phase with limited implementation at larger industrial scales, and there are uncertainties associated with carbon capture, transports and storage. A few studies have estimated the impacts of uncertainty on CCS performance for specific technologies (e.g. Roussanaly et al., 2020), and these calculate coefficient of variations between 0.1 and 0.25 for different uncertainty components (carbon capture, transport and storage). However, there is no information about the combined uncertainty. In the present study, the highest value of 0.25 is used.

The assumed emission reduction capacities and uncertainty measurements for the different emission reduction measures are summarized in Table 1.

The total maximum reduction in emissions corresponds to approximately 90% of the calculated emissions from fuel and food. The main part is obtained from reduction in emissions from fuel, which corresponds to 42% of the emissions. The potential of negative emission corresponds to 30% of the emissions.

Table 1
Maximum emission reductions and coefficients of variation (CV) for included abatement measures.

Abatement measures	Maximum abatement, mill. tonnes CO_2e	% of total BAU emission	CV in emission reduction
Food:			
Beef	2.61	9.56	0.13
Pork	0.56	2.05	0.13
Cheese	0.66	2.42	0.13
Milk products	0.75	2.75	0.13
Cream	0.32	1.17	0.13
Fuel:			
Gasoline	3.95	14.47	0.03
Diesel	7.47	27.36	0.03
Negative emissions:			
Forest management	2.05	7.51	0.42[a]
Afforestation	0.5	1.83	0.42[a]
Restoration of peatland	2.2	8.06	0.28
CCS[b]	3.45	12.64	0.25
Total	24.52	89.82	

Sources: Gren and Tirkaso (2020); [a] Gren and Carlsson (2013); [b] Johnsson et al., 2020 for maximum capacity and Roussanaly et al., 2020 for CV.

3.2. Costs of abatement measures

Costs are calculated for the three classes of abatement measures in each county. Costs of emission reductions by decreases in fuel and food are calculated as decreases in consumer surplus derived from linear demand functions. Quadratic cost functions for negative emissions are obtained from information on linear supply functions.

Decreases in consumer surplus are calculated as triangle areas between the optimal level of consumption and the BAU levels. The coefficient in the demand function is estimated by means of price elasticity and BAU levels of price and consumption of each good. The prices are taken at the national level and are therefore the same for all counties, since there are no county-level markets in Sweden that would equilibrate prices for these goods. For fuel, diesel, and gasoline, data on regional price elasticities and quantities were obtained from Tirkaso and Gren (2020). Regional data on quantities and elasticities of the food items are not available. Regional quantities of the food items are calculated by assuming that the consumption per capita is the same in all counties and corresponds to the average of Sweden (Statistics Sweden, 2020). Price elasticities on each food good is assumed to be the same in all regions and correspond to the national level elasticities (Säll and Gren, 2015).

The calculation of costs for forest management by delayed harvesting is based on Guo and Gong (2017), who derived supply curves for carbon sequestration by forests of Norway spruce in Sweden in a dynamic model of the timber market in Sweden. The cost of afforestation and restoration of drained peatland is calculated as the opportunity cost of land, which is approximated by linear supply functions of arable land. These are calculated based on data about supply elasticity of land, and BAU levels of the rental value of land and area of arable land and drained peatland. A linear supply function for CCS is calculated based on data on costs of CCS by Johnsson et al. (2020), who included cost of all three phases for facilities in Sweden.

3.3. Probabilistic constraints and distributional effects

Emissions from the consumption of fuel and food originate from fuel combustion and production of food in Sweden and abroad. According to SEPA (2020a), approximately 1/3 of emissions in the transportation sector take place abroad, and approximately 2/3 of the emissions from consumption of food originate from production abroad. Therefore, reductions in emissions from consumption of these commodities are not directly comparable with the Swedish climate targets, which refer to emission reductions in the country. For example, there are specific emission targets for the transportation sector and for all sectors, which are not part of the EU emission trading system. Because of this asymmetry between emissions from consumption and production, the imposed emission constraints in the current study range from zero to the assumed maximum abatement capacities in Table 1.

With respect to the choice of probability for achieving the target, there are no formulations for this decision in the Swedish climate action plans (MEE (Ministry of Environment and Energy), 2017). Although uncertainty in target achievement is acknowledged, there have been no explicit discussions about either definition of the uncertainty or acceptable deviation from the target. Calculations are made for a probability of 0.9, which was chosen by the only country, Canada, with explicit discussion of uncertainty (Kim and McCarl, 2009).

The CONOPT solver in the GAMS (General Algebraic Modeling System) modeling system for mathematical programming is used for solving all models (see Rosenthal, 2007 for further description). The Suits index for measuring distributional effects of the cost efficient solutions is calculated by relating regional abatement costs to gross regional product (GRP) in each county (Statistics Sweden, 2020).

4. Results

Minimum costs and equity outcomes are calculated with the costs, maximum abatement capacities, probability choice and distribution presented in Section 3. Since these quantifications rest on several assumptions, sensitivity analyses are presented in this section in order to examine the impact of costs from changes in the assumed values.

4.1. Costs of emission reductions

As a first test of the cost efficient allocation of emission reductions and negative emissions, we calculated the marginal costs at different levels for each class of measure (Fig. 2).

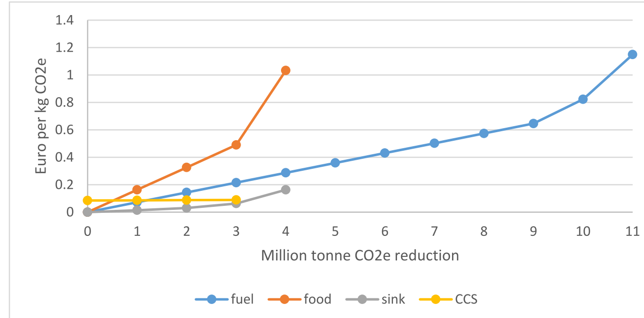

Fig. 2. Marginal costs of separate emission reductions in fuel and food consumption, carbon sink enhancement and CCS without uncertainty.

The curves in Fig. 2 have considerable differences in marginal costs and reduction capacities. Carbon sequestration has the lowest marginal cost at all reduction levels, and reduction in food consumption has the highest cost at reduction levels exceeding 0.5 million tonnes. As expected, emission reductions in fuel consumption show the highest reduction capacity because of the relatively large BAU emissions.

However, the consideration of uncertainty affects marginal costs in particular for carbon sequestration and CCS abatement because of the relatively large uncertainty as measured by the coefficient of variation in Table 1. The maximum reduction is reduced for all abatement measures and the marginal cost increases for each reduction level. The marginal cost for fuel reductions is increased by approximately 10%, but can increase by more than 500% for carbon sinks (see Appendix B, Table B1).

The total costs for different emission reduction levels under different assumptions of inclusion of negative emission measures and uncertainty are shown in Fig. 3.

As expected, costs increase at an increasing rate for all combinations of emission reduction options and uncertainty cases. Without negative emissions, the maximum reduction capacity is 60% because of constraints on minimum food and fuel consumption. The costs are lower at all reduction levels when negative emissions are introduced, and can correspond to less than half the cost for the same reduction level when only emissions from fuel and food are reduced.

The cost increases when uncertainty is included, and increases relatively more with negative emissions than without because of the higher uncertainty in these abatement measures. This is because of the increase in costs of the abatement measures with uncertain effect and the safety margin reduction needed to ensure the fulfillment of the probability constraint (i.e. $\phi^{\alpha}(\sigma)^{1/2}$in eq. (5)). This safety margin corresponds to approximately 15% of the emission target when all measures are included and the probability is 0.9 for achieving a 50% emission reduction.

4.2. Equity impacts

Suits index is calculated for emission reductions of 50% since this allows for the comparison of our cost estimates with other studies, which is made in Section 5. The calculated Suits index shows that the allocation of costs is regressive and it varies between −0.12 and − 0.17 depending on inclusion of negative emissions and consideration of uncertainty (Fig. 4).

Without uncertainty, the Suits index decreases when negative emissions are included. The introduction of negative emissions reduces the share of abatement costs for counties with high income shares and high emissions from fuel and food (such as Stockholm), and increases the cost share for counties with low income share with high capacities of negative emissions (in particular, northern Sweden). The impact of negative emissions on the Suits index is reduced when considering uncertainty since the increases in emission reductions created by the safety

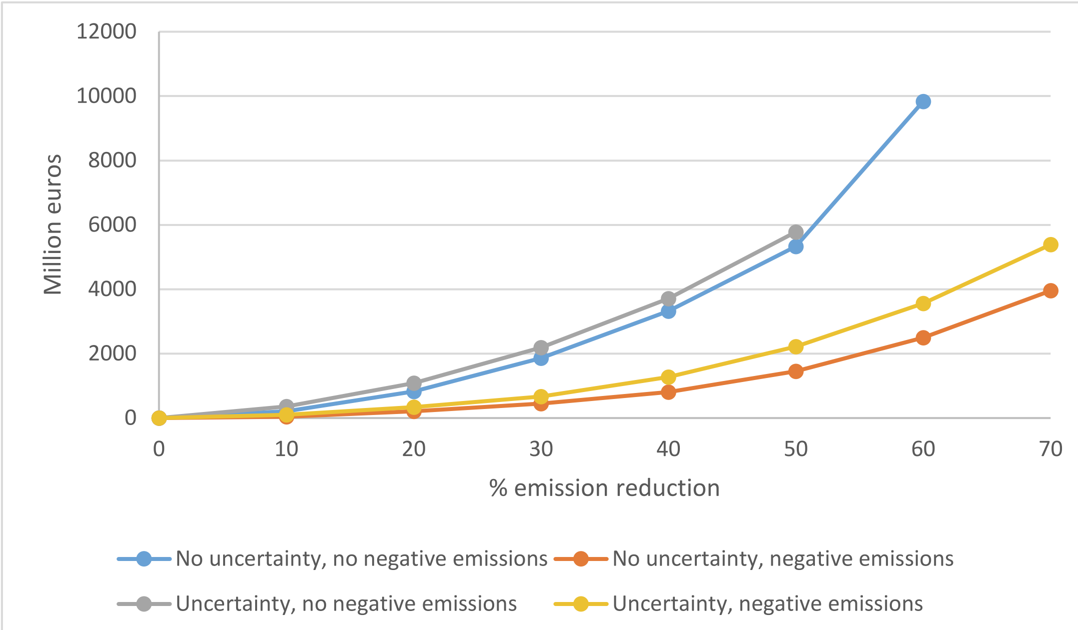

Fig. 3. Minimum costs for reaching different reductions in total emissions from food and fuel with and without uncertainty and negative emissions, prob. = 0.9 with a normal distribution.

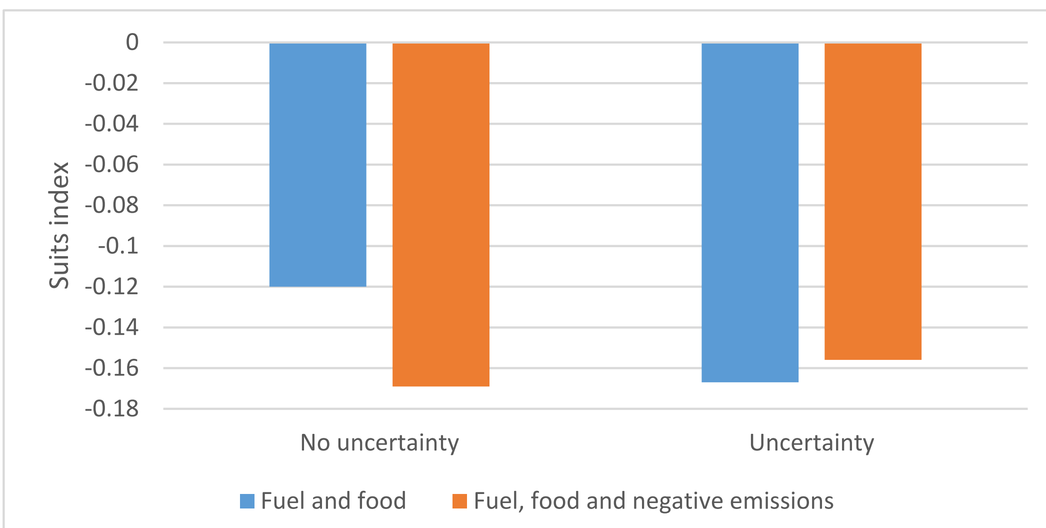

Fig. 4. Suits index at cost efficient reduction of emissions by 50% with and without negative emissions and uncertainty (prob = 0.9).

requirements are obtained by reducing emissions from fuel and food in counties with high shares of total GRP.

The minimum cost in relation to the Swedish gross national product varies between 0.31% and 1.23% for a 50% emission reduction, but the variation is large between the counties. At the 50% emission reduction and a chosen probability level of 0.9, the cost in relation to GRP is lowest for Stockholm under all cases with and without negative emissions and uncertainty (Fig. B2 in appendix B). It varies for this county between 0.11% and 0.67% depending on inclusion of uncertainty and negative emission. However, for low income counties, the highest cost exceeds 1.5% of GRP, which is reduced by at least one third when negative emissions are allowed.

4.3. Sensitivity analysis

Sensitivity analyses are made for an alternative probability distribution, choice of reference income in the calculations of Suits index, and parameter values on reliability levels, uncertainty quantifications, costs, and abatement capacities. Costs and equity are calculated for all changes of a 50% emission reduction with and without uncertainty.

An alternative to the normal probability distribution is the more flexible distribution, Chebyshev's inequality, without assumptions about the shape of the probability distribution. $\phi^{\alpha}$is then determined according to $\phi^{\alpha} = 1/(1-\alpha)^{1/2}$ (see McCarl, 2010 for more details). The level of ϕ^{α} for $\alpha = 0.9$ is then 3.16, which is considerably larger than for the same probability choice with a normal distribution.

The Suits index is calculated for disposable income as an alternative to GRP as a reference point. This measurement accounts for tax payments and transfers within and between counties and provides the basis for the consumption ability, which is often used as a proxy for lifetime incomes (e.g. Sterner, 2012).

Table 2
Sensitivity analysis of minimum costs and Suits index at 50% emission reduction with and without uncertainty (prob = 0.9).

	Minimum costs, million euros;		Suits index;	
	No uncertainty	Uncertainty	No uncertainty	Uncertainty
Reference case	1457	2217	−0.168	−0.156
Chebyshev prob. distribution		3852		−0.125
Disposable income as reference for Suits index			−0.116	−0.104
Changes with ±10% in[a];				
Reliability level[b]		1943, 2994		−0.161, −0.142
Uncertainty, CV[c]		2166, 2267		−0.157, −0.157
-Costs of fuel and food	1357, 1541	2058, 2376	−0.169, −0.166	−0.157, −0.156
Costs of negative emissions	1395, 1521	2154, 2280	−0.166, −0.169	−0.093, −0.157
Capacity of negative emissions	1631, 1327	2399, 2062	−0.159, −0.151	−0.150, −0.160

[a] The first number in each column for the 10% changes from the reference level shows effect of a reduction, and the second effects of an increase. For example, a 10% decrease in costs of fuel and food reduces total cost to 1357 million euros, and an increase raises them to 1541 million euros; [b]prob. = 0.81 and prob. = 0.99; [c]changes in coefficient of variation (CV) from reference values in Table 1.

Calculations are made for relatively small changes, ±10%, in the reference values of reliability level, uncertainty, and abatement costs and capacities in order to examine the existence of large impacts on costs and equity (Table 2).

As expected, the costs are high with the Chebyshev probability distribution because of the large safety margin. It can also be noted that the regressivity is reduced, which is due to the need for more abatement by reductions in consumption of fuel and food which mainly takes place in the rich counties with large population sizes, such as the Stockholm county. The reduction in regressivity when using disposable income as the reference point is also expected since transfers and tax payments even out differences in GRP.

Regarding the 10% changes from reference values, the effects on costs are largest for the increase in the reliability level and the impact on equity is highest for a decrease in the cost of negative emission. The increase in reliability to prob. = 0.99 raises the need for safety margin since the standard normal increases from 1.28 to 2.36. The decrease in abatement costs of negative emissions reduces the relative cost burden for low income counties with high access to negative emissions, and thereby the regressivity in the allocation of costs between counties. In general, the relative effects of changes in other abatement costs are low and never exceed 12% deviation from the reference values of the costs and Suits indices in the reference case. Similar results are obtained for the 10% changes in the abatement capacities. The 10% changes in the capacity of emission reduction of fuel and food from the reference levels did not affect the results since both levels were above the cost efficient solution for these options.

5. Discussion

The main purpose of this study was to calculate and compare costs and distributional effects (in Sweden) of reducing emissions from the consumption of fuel and food, increasing negative emissions and also accounting for uncertainty. One major result was that the marginal cost of reduction in food consumption is highest, which can be more than ten times higher than the marginal cost of negative emissions. Considering uncertainty raises the marginal cost of negative emissions relative to the other measures, but total minimum costs are still lower at all emission reduction levels when negative emissions are included as opposed to when they are excluded. This finding support results from other studies (see Raihan et al., 2019 for a review).

Another major result was that the introduction of negative emissions can increase the regressivity of the allocation of cost among regions, since abatement measures are located in counties with low income and relatively high capacity for these measures. Similar findings were obtained by Munnich Vass et al. (2013) for emissions reductions with and without carbon sequestration at the EU level. The consideration of uncertainty reduces the degree of regressivity, because the safety margin raises the reduction requirement which is met by reductions in fuel and food consumption in relatively rich counties.

Sensitivity analyses indicated that the cost estimates were most sensitive to changes in parameter values in the chosen model when uncertainty was considered. Then, costs could increase by 75% from the reference level depending on assumption of probability distribution, reliability level, and costs of negative emissions. Without uncertainty, the results were relatively robust. However, the results depend on, not only to the choice of parameter values in the chosen models, but also on the simplification made by excluding dispersal and dynamic considerations. It can therefore be of interest to compare our results with other studies, but the lack of studies including the same measures as in the present study implies that only partial comparisons can be made.

Calculations have been made on cost efficient emission reductions in transports in Sweden (SNIER (Swedish National Institute of Economic Research), 2019; Tirkaso and Gren, 2020) and emission reductions in sectors that do not participate in the EU emission trading system (SNIER (Swedish National Institute of Economic Research), 2017). SNIER (Swedish National Institute of Economic Research) (2019) used a general equilibrium model of Sweden which accounts for dispersal effects in the economy and calculated the necessary increase in fuel prices for a cost efficient achievement of the Swedish emission target for transports of a maximum emission corresponding to 30% of the total CO_2 emissions in 2010 (to be achieved in 2030). The results suggested that a fuel price increase of approximately 200% would be necessary. Tirkaso and Gren (2020) used a model similar to the present study and showed that the necessary fuel price increase to achieve the same target is between 130% and 280% depending on the assumption of short and long run price elasticities. In the present study, the estimated marginal cost of achieving this reduction target (11 million tonnes of CO_2e) amounts to 1.149 euro/kg CO_2. This implies increases in the prices of fuel in 2018 by 165% for gasoline and 180% for diesel would have been needed.

SNIER (Swedish National Institute of Economic Research) (2017) used a general equilibrium model of Sweden and calculated the minimum cost of reducing emissions from the non-trading sector (which includes transports and agriculture) by 50%, which corresponded to 2% of the Swedish gross national product (GNP). In our study, the costs of reducing emissions by 50% by decreasing emissions from fuel and food consumption without consideration of uncertainty correspond to 1.1% of GDP in 2018. Our lower estimate can be partly explained by our disregard of dispersal effects. Admittedly, the cost estimates are not quite comparable, because SNIER (Swedish National Institute of Economic Research) (2017) considered territorial emissions and our study included emissions from consumption that occurred both in Sweden and in countries of origin for imports.

Our results can also be compared with the few studies assessing effects of introducing the current Swedish carbon tax (0.115 euro/kg CO_2e) on food consumption in Sweden (Säll et al., 2020; Gren et al., 2021). Both studies introduced the tax on animal and vegetable products, but with different models. Säll et al. (2020) used a similar approach as in the present study and found that the tax reduced emissions from consumption by 10%. Gren et al. (2021) used a partial equilibrium model of the agricultural sector, which accounts for adjustments by consumers and producers to the introduction of the tax. The results showed a reduction in emissions from food consumption by 4.4%. In this study, the effects of introducing a carbon tax of 0.115 euro/kg CO_2e can be assessed from the marginal costs shown in Fig. 1, which indicates a reduction in emission from food consumption by approximately 7%. The lower reduction showed in Gren et al. (2021) is explained by consideration of producer responses, which implies that the burden of the tax will be shared between producers and consumers. In Säll et al. (2020) and in this study, it was assumed that the entire tax affects consumers by increases in prices.

With respect to dispersal effects of negative emissions, the direction and magnitude of these effects are less clear. Enhanced carbon sequestration by changes in forest management may increase the competition for feedstock by the forest industry and for bioenergy by society. Increased competition for woody material will raise input and output prices, but in the case of Sweden, it is shown in a partial equilibrium model of the forest sector that the welfare effects of increased competition are relatively small since the increased output prices counteract the increase in costs from high input prices (Olofsson, 2018). On the other hand, afforestation is likely to increase the supply of woody material, and have little effect on agriculture since it is assumed that afforestation takes place on impediment agricultural land. This is not the case for restoration of peatland, which will reduce supply of food goods and thereby increase the prices, which are likely to be minor since Sweden is a part of the EU agricultural markets. The introduction of CCS will increase the production costs of the sectors, but there is no study calculating dispersal effects in the Swedish economy.

While disregard of dispersal effects is likely to underestimate costs, the static nature of the model may instead overestimate the cost since, in the long run, there are more adjustment possibilities in the consumption patterns and technological development of negative emissions. In general, the long run price elasticities for fuel are higher in absolute terms and short run (e.g. Dahl, 2012), which reduce the cost as measured by consumer surplus in this study. Technological development may decrease the cost and capacities of CCS, and forest carbon sequestration increases over time for, in particular plantation of trees. Another aspect is that for a target to be obtained in the future, costs decrease, not only from the choice of abatement measures, but also through the timing of measures since the discount rate promotes delay of implementation of measures as much as possible for reaching the target. This option is likely to favor measures with relatively rapid response such as reduction in fuel and food consumption, since they can be implemented late. On the other hand, there can be delays between the implementation of negative emissions, such as restoration of drained peatland, and their full effect which necessitates early implementation and thereby relatively high cost.

6. Conclusions

One of the main conclusions from this study is that the marginal cost of a reduction in food consumption is twice as large as for reductions in emissions from fuel transport, and 10 times the marginal cost of carbon sequestration. Consideration of uncertainty, which is particularly important for negative emissions, reduces the relative differences in marginal costs. Despite the simple model (chosen to account for uncertainty) used to calculate costs, the results are relatively close to the results of other comparable studies using other models when uncertainty is not considered. Similar to the results in many national and international studies, it was shown that the introduction of options for negative emissions reduces the cost for a given emission reduction, but the cost increases when uncertainty is considered. Sensitivity analyses indicated considerable impacts on minimum costs of emission reductions depending on the choice of probability distribution and reliability level.

Another main conclusion concerns the distributional effects of negative emissions and uncertainty. While all cases showed slightly regressive outcomes in the allocation of costs among counties, the introduction of negative emissions increased the regressivity since access to negative emissions is high in low income counties. Consideration of uncertainty reduced the regressive impact since the safety margin implied an increase in abatement in high income regions with large emissions from fuel. A change from GRP to disposable income as the reference income for calculating Suits index reduced the regressive effect since transfer and tax payments even out differences in income between the counties.

The empirical results are specific for Sweden, but the qualitative conclusions regarding the differences in abatement costs are likely to be valid for other countries and regions. The high costs for reductions in food and fuel consumption were determined by the low price elasticities for the goods, which have been found for several other countries (see Dahl (2012) for a review of fuel price elasticities and Andreyeva et al. (2010) for a review of food price elasticities). The relatively low cost for negative emissions, in particular carbon sink enhancement in forests, has been demonstrated in several studies (review in Raihan et al., 2019). It has also been shown that the introduction of forest carbon sequestration within the EU climate policy would reduce cost for meeting 2030 emission targets, but also be regressive because of the large gains from cost savings for relatively rich countries (Munnich Vass et al., 2013).

These findings have some interesting policy implications. One is that achieving climate targets by reducing food and fuel consumption can be quite costly, but that including negative emissions (which currently play a minor role in climate mitigation in Sweden and many other countries but is promoted in the European Green Deal (EC, 2021)) reduces the cost burden considerably. On the other hand, negative emissions may contribute to increases in the regressivity of the allocation of costs between counties, which may be an impediment for acceptance and implementation of the low cost program. This potential regressivity could be mitigated if income from carbon taxes on emissions from fuel and food were used to pay for negative emissions. Since negative emissions are costly for firms and land owners, they are likely not to be implemented without some type of compensation.

Environmental tax refund systems that compensate firms for investing in environmental improvements have been suggested in the literature and implemented in practice in several countries (e.g. Millock and Nauges, 2006; Sterner and Höglind-Isaksson, 2006; Gren et al., 2021). Going by the results from this study, a tax refund system would be based on using CO_2 taxes on food and fuel to subsidize negative emissions. The low price elasticity of fuel and food not only implies that there will be high costs for reducing consumption in order to reach certain emission reduction targets, but would also generate considerable tax revenues. However, the magnitude of tax revenues and abatement costs would indeed be sensitive to the choice of reliability level and probability distribution, in particular if options for negative emissions are allowed in the abatement program. This points out the need for transparency with regard to the choice of reliability levels in target setting and measurement of uncertainty in emission reduction by different measures.

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Appendix A. Derivation of emission constraints, first-order conditions and Suits index

Emission constraint

Chance-constrained programming is used to solve the cost-minimization problem with a probabilistic constraint (Taha, 1976). Eq. (3) is then transformed into a deterministic equivalent by normalizing the expression in parentheses on the left hand side of eq. (3) according to:

$$prob\left[\frac{G-\mu}{(\sigma)^{1/2}} \le \frac{\overline{G}-\mu}{(\sigma)^{1/2}}\right] \ge \alpha \tag{A1}$$

where the mean $\mu = E[G]$ with E is the expectation operator, $\sigma = Var(G)$ and the term $\frac{G-\mu}{(\sigma)^{1/2}}$ shows the number of standard errors at the chosen probability ϕ^α by which G deviates from the mean. By the choice of α, there is a level of acceptable deviation ϕ^α and the expression in brackets in eq. (3) then holds only if:

$$\mu + \phi^\alpha(\sigma)^{1/2} \le \overline{G} \tag{A2}$$

First-order conditions

The cost minimization problem defined by eq. (4) is solved by forming the Lagrange expressions:

$$\begin{aligned} L = \sum_c \left(\sum_t C^{ct}(A^{ct}) + \sum_f C^{cf}(A^{cf}) + \sum_k C^{ck}(A^{ck}) \right) - \lambda\left(\overline{G} + \mu - \phi^\alpha(\sigma)^{1/2}\right) + \\ \lambda^{ct}\left(\overline{A}^{ct} - A^{ct}\right) + \lambda^{cf}\left(\overline{A}^{cf} - A^{cf}\right) + \lambda^{ck}\left(\overline{A}^{ck} - A^{ck}\right) \end{aligned} \tag{A3}$$

The first-order conditions for a cost effective solution are:

$$\frac{\partial C}{\partial A^{it}} = \frac{\partial C^{it}}{\partial A^{it}} - \lambda\left(\frac{\partial \mu}{\partial A^{it}} - \frac{\theta^\alpha}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{it}}\right) - \lambda^{it} = 0 \tag{A4}$$

$$\frac{\partial C}{\partial A^{if}} = \frac{\partial C^{if}}{\partial A^{if}} - \lambda\left(\frac{\partial \mu}{\partial A^{if}} - \frac{\theta^\alpha}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{if}}\right) - \lambda^{if} = 0 \tag{A5}$$

$$\frac{\partial C}{\partial A^{ik}} = \frac{\partial C^{ik}}{\partial A^{ik}} - \lambda\left(\frac{\partial \mu}{\partial A^{ik}} - \frac{\theta^\alpha}{2\sigma^{1/2}}\frac{\partial \sigma}{\partial A^{ik}}\right) - \lambda^{ik} = 0 \tag{A6}$$

Solving for λ in eqs. (A4–A6) and equalizing gives the condition in eq. (6).

Appendix B. Table B1, Fig. B1-B2

Table B1
Marginal costs for separate reductions in emissions of fuel and food, and carbon sequestration and CCS for different reduction levels at the probability level of 0.9 with a normal probability distribution, euro/kg CO_2e.

CO_2e reduction, mill. tonnes	Fuel	Food	Carbon sink	CCS
0	0	0	0	0.085
1	0.092	0.198	0.04	0.133
2	0.183	0.396	0.21	0.136
3	0.275	0.594		
4	0.366	2.525		
5	0.459			
6	0.554			
7	0.648			
8	0.744			
9	0.846			
10	0.971			

Fig. B1. Counties in Sweden. Source: www.lansstyrelsen.se

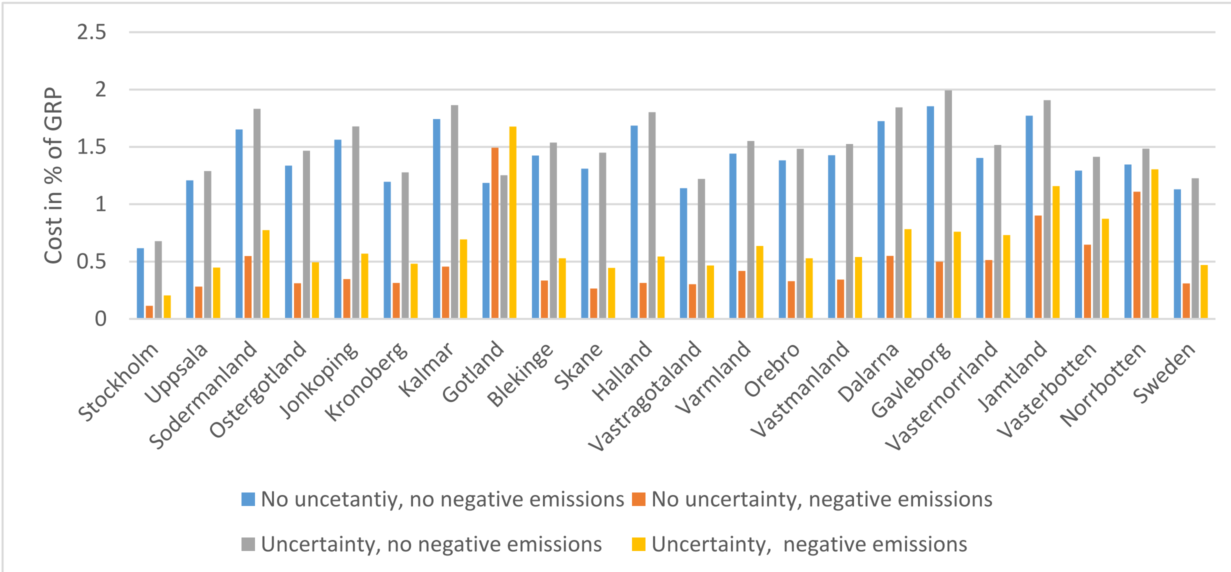

Fig. B2. Cost efficient allocation of abatement cost in % of GRP for different counties and for Sweden as a whole (in % of GDP) with and without negative emissions and uncertainty.

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