Cost- benefit analysis of climate policy and long term public investments

To Billie, Alice and Olle

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Cost- benefit analysis of climate policy and long term public investments

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Abstract

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This compilation dissertation consists of four essays with the common theme of welfare analysis of long-term public investments. The first two essays focus on analysis of climate change mitigation, i.e., the social cost of carbon dioxide. The third essay focuses on cost-benefit analysis (CBA) of transport investment projects, while the last essay takes a broader perspective on welfare analysis.

Essay 1: *The Temporal Aspects of the Social Cost of Greenhouse Gases*. The purpose of Essay 1 is to investigate the temporal aspects of the social cost of greenhouse gases. I find that the calculation period should ultimately be modeled to be consistent with the discount rate and that the "global-warming potential" concept is unsuitable for calculation of the social cost of GHGs other than carbon dioxide.

Essay 2: *Avoiding path dependence of distributional weights: Lessons from climate change economic assessments*. In Essay 2, I explore shortcomings in income weighting in evaluation of climate change policy. In short, in previous versions of two of the most important existing models, regional economic growth is double counted. The proposed alternative approaches yield about 20–40% higher values of $SCCO_2$ than the old approach.

Essay 3: *Does uncertainty make cost-benefit analyses pointless?* In Essay 3, the aim is to investigate to what extent CBA improves the selection decision of projects when uncertainties are taken into account, using a simulation-based approach on real data of infrastructure investments. The results indicate that, in line with previous literature, CBA is a rather robust tool and considerably increases the quality of decision making compared with a random selection mechanism, even when high levels of uncertainty are considered.

Essay 4: *Household Production and the Elasticity of Marginal Utility of Consumption*. In Essay 4, I develop a new model to show that omission of household production in a previous model leads to bias when the elasticity of marginal utility of consumption, EMUC, is estimated. I further offer new, unbiased estimates based on current evidence of the included parameters, suggesting a lower bound of EMUC at about 0.9.

Keywords: Social Cost of Carbon; Greenhous Gases; Distributional weights; Discounting; Cost benefit analysis; Elasticity of Marginal Utility of Consumption; Risk aversion

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Table of Contents

List of Essays

1 Introduction

1.1 Short summary

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1.2 Background and motivation

Some decisions are inherently complex in that they involve multiple conflicting goals, where the value of each goal in turn depends on multiple factors that need to be estimated. In such circumstances, a means to increase transparency and comprehensibility in decision making is through explicit, formal structuring of the problem at hand. Cost-benefit analysis (CBA) offers a framework for such formal structuring of decisions. A CBA consists of three basic elements: (1) forecasts of exogenous physical quantities, e.g., emissions projections, (2) mathematical relationships between quantities, e.g. the effect of emissions on atmospheric concentrations, and (3) valuation of quantities, e.g., monetary valuation of reductions in commuting times. Typically, all these elements are subject to uncertainty, which is why sometimes a fourth category is included: random variables. When all elements are properly assessed, CBA can inform decisions and answer questions like: Does the benefits of a potential investment exceed the costs? Which subset of potential projects, given a scarce budget, is most likely to maximize total benefits? Which is the optimal level of carbon tax if the objective is to maximize wellbeing of both current and future generations?

The present dissertation is dedicated to improvement of current CBA practice for long-term public investments, as well as to enhance the understanding of mechanisms in such models. In CBA of public investments, welfare theory is the foundation of valuation of costs and benefits. In social choice making, a starting point is to only select alternatives that are Pareto optimal, i.e., alternatives where it is not possible to increase the welfare of some individuals without reducing the welfare of others. However, most often, there are multiple Pareto-optimal solutions, and thus additional selection criteria are usually needed.

It is often assumed that total welfare in society can be expressed as a function of all n individuals' utilities, which in turn are functions of their consumption:

$$W = W(U_1(c_1), U_2(c_2), \ldots, U_n(c_n)) \,, \tag{1}$$

where W is the total welfare in society, U_i is the utility of individual i, and c_i is the consumption of individual i. This means that the marginal change in total welfare in society from an increase in individual i's income can be expressed as:

$$\beta_i = \frac{\partial W}{\partial c_i} = \frac{\partial W}{\partial U_i} \cdot \frac{\partial U_i}{\partial c_i}. \quad (2)$$

Here, $\frac{\partial W}{\partial U_i}$ refers to the social welfare weight that society assigns to each individual and $\frac{\partial U_i}{\partial c_i}$ is the marginal utility of consumption. The combined factor β_i will here be referred to as the distributional weight.

The Kaldor–Hicks criterion is a measure of economic efficiency that captures some of the intuitive appeal of Pareto efficiency but is less stringent and hence applicable to more circumstances. Under Kaldor–Hicks efficiency, an outcome is considered more efficient if a Pareto-optimal outcome can be reached by arranging sufficient compensation from those who are made better off to those who are made worse off so that everybody ends up no worse off than before. In line with the Kaldor-Hicks concept, Harberger (1978) argued not to use distributional weights in the CBA of a specific project if it possible to find a more efficient redistribution mechanism outside the project. Therefore, in CBA of for example national infrastructure projects, the distributional weights are often set to 1. It is also standard practice to assume that utilities of individuals are additive, so that:

$$W = \sum c_i. \quad (3)$$

In some cases, e.g., CBA of climate change mitigation, redistribution is complicated to the extent that optimal redistribution may not even be possible. This restriction provides a basic rationale for the use of distributional weights in this setting. When distributional weights are applied, the standard assumption is that all individuals have the same utility function and the same individual weight in the welfare function, $\frac{\partial W}{\partial U_i} = 1$, so that $\beta_i = \frac{\partial W}{\partial c_i} = \frac{\partial U_i}{\partial c_i}$ is the income weight.

The utility function of an individual is usually defined in the positive quadrant and concave, reflecting the rule of diminishing marginal utility. EMUC is the parameter that determines how fast marginal utility decreases with consumption. It is defined as:

$$\eta = -\frac{c \cdot U''(c)}{U'(c)}. \quad (4)$$

Comparisons of costs and benefits over time require a discount rate, which determines the weight placed on costs and benefits occurring at different times. For a continuous specification of time, the welfare in each time period of one representative agent is generally assumed to be:

$$W_t = U\big(c(t)\big) \cdot e^{-\delta} , \tag{5}$$

where δ is the pure rate of time preference (PRTP). It is also common to include the utility function in the discount rate, so that eq. (5) transforms into:

$$W_t = c(t) \cdot e^{-rt}, \tag{6}$$

where r is the discount rate, generally assumed to depend on the PRTP and expectations of future incomes. If we believe that future generations will be richer, it is perfectly rational and ethical to place less weight on their marginal income, due to diminishing marginal utility. As a result, the discount rate will depend strongly on the expected future economic growth and to what extent we weight benefits and damages based on the receivers' income (i.e., the value of η). The Ramsey rule of discounting can be seen as simple and effective way to approximate (5) through (6):

$$r = \delta + \eta g, \tag{7}$$

where r is the discount rate, δ is the pure rate of time preference (PRTP), η is EMUC, and g is the growth rate in income per capita. If PRTP is set low, the main part of the discount rate will be due to the second term in the Ramsey formula, which accounts for intergenerational equity. Hence, accurate estimation of EMUC is of crucial importance for valuation of cost and benefits that occur in the far future, such as damages related to climate change. In the last essay of this compilation dissertation, *Household Production and the Elasticity of Marginal Utility of Consumption*, a new method to increase the accuracy of such estimation is proposed.

One way to account for uncertainty in CBA analyses is through Monte Carlo simulation. Instead of defining variables as their most likely value, they are defined as random variables, i.e., variables that can take a range of values according to their probability distribution. The CBA analysis is then repeated a large number of times, and each time different values of the random variables are drawn. As a consequence, results will not be in the form of a single value but rather in the form of a distribution of values, from which statistical measures such as mean value and standard deviation can be drawn. The PAGE2002 model, which is used in Essays 1 and 2, relies on Monte Carlo simulation. In Essay 3, *Does uncertainty make cost-benefit analyses pointless?*, Monte Carlo simulation is utilized in a more direct way, as a core part of the method. There it is used to explore the usefulness of CBA on a fundamental level, as a ranking criterion of potential investments.[1]

Two of the essays in the dissertation are devoted to the benefits of mitigation of climate change, i.e., the social cost of carbon dioxide ($SCCO_2$), which is the cost of the damage caused by emitting one additional unit of carbon dioxide (CO_2), typically expressed in U.S. dollars per metric tons of CO_2. Ethical considerations regarding the time preference and distributional weights, on which there is presently no consensus, have a great influence on the results. Since 1982, when the first $SCCO_2$ estimate was presented (Nordhaus, 1982), hundreds of estimates have been produced by researchers using different integrated assessment models (IAMs). The essential linkages in all models are from emissions to atmospheric concentration, from concentrations to temperature change, and from temperature change to damages. Although there has been strong progress in the sophistication and comprehensiveness of these models, there are still shortcomings to tackle and omitted factors to include. Essay 1, *The Temporal Aspects of the Social Cost of Greenhouse Gases*, is one small increment on the path to more sophisticated and accurate models, as well as to a greater understanding of the mechanisms in such models. In Essay 2, *Avoiding path dependence of distributional weights – Lessons from climate change economic assessment*, a more serious shortcoming in two of the most prominent models in this area is addressed and a solution proposed.

1.3 The scope of the dissertation

The scope of the dissertation starts out rather narrow and results-oriented in Essay 1, *The Temporal Aspects of the Social Cost of Greenhouse Gases*, but gradually expands as each of the subsequent essays goes deeper into the founding method of those results. In Essay 1, the focus is on both numerical results, from one specific model, and some minor methodological issues of technical nature. In Essay 2, *Avoiding path dependence of distributional weights – Lessons from climate change eco-*

[1] For a more thorough introduction to welfare calculations and CBA, see Boadway (2006).

nomic assessment, there is a focus on a more fundamental methodological issue of IAMs, and the few numerical results included are used more as an illustration. Essay 3, *Does uncertainty make cost-benefit analyses pointless?,* takes a broader perspective of CBA, not restricted to climate change mitigation. In essence, Essay 3 explores what rational justification there is to use CBA as a selection criterion among conflicting potential investments. Finally, in Essay 4, *Household Production and the Elasticity of Marginal Utility of Consumption*, I turn to the welfare theory that is the foundation of the CBA framework for public investments. Here I propose a new method to estimate one of the most central parameters in such economic theory.

2 The essays

2.1 Essay 1

The Temporal Aspects of the Social Cost of Greenhouse Gases

The social cost of carbon dioxide ($SCCO_2$)[2] is the cost of the damage caused by emitting one additional unit of carbon dioxide (CO_2), typically expressed in U.S. dollars per metric ton of CO_2. It is known that the temporal aspects are of great importance for such calculations, but most of the focus until now has been on discounting. In this study, I examine the temporal aspects in more depth and focus on the interactions between different temporal aspects using the PAGE2002 model[3].

A number of studies have shown that $SCCO_2$ is highly sensitive to discounting. There have also been studies exploring how $SCCO_2$ develops over time (notably Marten and Newbold, 2012), and they have generally found an increasing trend. Yet a few other studies look at the relationship between the social cost of greenhouse gases (GHGs) with different atmospheric lifetimes. However, explicit comparisons of the growth rate of different GHGs with respect to discount rate have to my knowledge not been performed, nor has the impact of calculation period been explored.

The purpose of Essay 1 is to investigate the temporal aspects of the social cost of GHGs. I am particularly interested in the interaction between time of emission, discounting, and type of GHG (where different GHGs differ in atmospheric lifetime). Two particular questions that I aim to answer are how the calculation period should be set and whether global warming potentials (GWPs) can be used to calculate the social cost of GHGs other than CO_2.

Two aspects of social costs of CO_2 are explored: the sensitivity to discounting parameters and the influence of calculation period. First, a partial sensitivity analysis of $SCCO_2$ with respect to PRTP and EMUC is performed. Second, the influence of the calculation period for $SCCO_2$ is examined. In addition, two aspects of different GHGs are analyzed, in each case with two different discount schemes: social costs and global damage

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[2] Often the term social cost of carbon, SCC, is used in the literature, which refers to the social cost of emitting one mass unit of pure carbon into the atmosphere in the form of carbon dioxide. One mass unit of carbon results in 3.66 mass units of CO_2.

[3] For a specification of the model, see Hope (2006).

potentials, and growth rate over time. Analyses are performed for CO_2, methane (CH_4), and sulfur hexafluoride (SF_6).

The main conclusions are that the calculation period should ultimately be modeled to be consistent with the discount rate and that GWPs cannot be used to calculate the social cost of GHGs other than CO_2. The latter might be especially important when it comes to short-lived GHGs.

Most models have a fixed time horizon that is chosen to be appropriate for the default discount rate of each model. The results of the present study show that if the discount rate is radically altered, the results may by heavily truncated by the default choice of time horizon. As a solution I propose that time horizon ultimately should be modeled as a function of the discount rate. If the proposed method leads to calculation periods that are perceived to be unreasonably long, the discount rate should be reconsidered.

The analyses of global damage potentials largely confirm results and conclusions from previous studies on this issue, notably Marten and Newbold (2012) and Waldhoff et al. (2014). However, I further show that discounting is an important driver of increases in the social cost of GHGs. In addition I have noted that the global damage potentials of sulfur hexafluoride sometimes behave in the opposite direction from what is expected when temporal parameters are varied. This phenomenon occurred both in the present study and in Waldhoff et al. (2014), and thus warrants further investigation in the future.

2.2 Essay 2

Avoiding path dependence of distributional weights:
Lessons from climate change economic assessments

In some cost-benefit analysis (CBA) applications, e.g., valuation of climate change damages, weights are used to account for diminishing utility of marginal income. This is usually done by means of intra-temporal distributional weights, which are combined with discounting to account for both inter-temporal equity and efficiency. Previously, two of the leading models used for valuation of climate change mitigation suffered from a serious specification problem with respect to these issues, which I will theoretically show in this essay.

As a numerical illustration of the problem, the PAGE2002 model is used. In this model, equity is accounted for in the following manner: First, distributional weights are applied for each region based on the mean GDP/capita in each time period, independently of other time periods, so that inter-temporal equity at this stage is ignored. Inter-temporal equity is instead accounted for in the next step by discounting, using the Ramsey rule. This is done for each region separately, based on each region's expected economic growth path. Anthoff et al (2009) noted that the FUND model (another IAM) previously used a method similar to PAGE2002 and that this method was incorrect. They introduced a new method to correct for the previous problems, but they did not show why the method would leads to inconsistencies. In my study I show why an inconsistency problem may arise for a more generalized model, and then I derive a general solution to the problem.

The same theoretical solution has been found independently in a working paper by Richard Tol, (2015). However, in that work, focus was only at the new method, and not at all the previous inconsistency problem. Also, in the present analysis I use a more general utility function as a base, from which I derive the results, hence, the common results from Tol (2015) are based on a plausible special case of this more general specification. In addition, I use another model for the numerical results; the PAGE2002 model, instead of the FUND model. Moreover, in a recent, peer-reviewed article by Tol et al., the base case specification in the FUND model, (see Waldhoff et al., 2014), is still flawed, even though in a slightly different way than before. Although denoted as using no equity weights, in practice this approach implies regressive distributional weights, as show in Essay 3.

The analysis consists of two sections. In the theoretical section, I set up a general model to show that a path dependence problem exists and how it comes about, and I also offer a solution to the problem. The general requirement for an inconsistency problem to occur is when intra-temporal distributional weights are applied along with discounting, based on region-specific growth-based discounts rates, in two separate steps. In the numerical section, first a very simple example is set up to show intuitively how the basic features of the model laid out in the theoretical part work. Secondly, I use the PAGE2002 model to estimate the magnitude of the inconsistency problem.

It is estimated that the inconsistency problem in the original model eliminates the influence of distributional weights on the $SCCO_2$ compared with a standard CBA approach where equal distributional weights and no region-specific discount rates are used. The proposed alternative methods would result in about 20–40% higher $SCCO_2$ values than the original model.

The sensitivity of $SCCO_2$ to different weighting procedures is considerable but not extreme compared with other sources of uncertainty, such as the discount rate and climate sensitivity. The analysis shows that it would be worthwhile to handle equity more properly when it comes to climate economics since after all, a difference of 20% in a carbon price adds up to huge amounts on a global scale.

In a broader context, this article brings attention to an issue that to my knowledge has never been addressed in the CBA literature. This issue, i.e., combining discounting and distributional weighting correctly, has the potential to be important in all long-term decisions where distributional weighting is present.

2.3 Essay 3

Does uncertainty make cost-benefit analyses pointless?

Co-authored with Jonas Eliasson, KTH Royal Institute of Technology.

In public decision making, for example regarding infrastructure investments, CBA is frequently used to systematically compare costs and benefits of various projects. Such analyses are based on forecasts of likely future scenarios, with and without the project in question. These forecasts are obviously subject to uncertainties, and so are the valuations of costs and benefits of the respective projects. Such fundamental uncertainties have led many researchers and policy makers to question the usefulness of CBA as a basis for public decision making. For example, Flyvbjerg (2009) criticizes CBA as a selection criterion based on the lack of precision in forecasts of investment costs and transport demand. He argues that the errors in forecasting are of such magnitude that CBAs will "with a high degree of certainty be strongly misleading," concluding with the words, "Garbage in, garbage out" (p. 348).

But will this intuitively persuasive argument hold up in reality? In Essay 3 we aim to answer this question by investigating how robust the policy recommendations of CBAs of infrastructure investments are with respect to several kinds of uncertainty. We use a simulation-based approach based on real data to explore how uncertainties affect selection of investments under a given budget, and how they hence affect the total achieved net benefits of the resulting investment portfolio. This is compared with both the ideal selection (under no uncertainty) and a random selection of investments from the list of candidates. The latter comparison represents a choice situation where decisions are made without any consideration of CBA results. In fact, previous research has found that politicians' investment selections are virtually indistinguishable from random selection from the list of investment candidates, and that the transport administrations' compilations of investment candidates (which are done before CBAs are made) indicate that it is very difficult, even for professionals, to assess cost-efficiency of investments without CBA results (Eliasson et al., 2015; Eliasson & Lundberg, 2012).

We study the sensitivity of selection and realized total benefits with respect to uncertainties in forecasts of investment costs, transport demand, assessment of effects, and valuations of benefits (travel time savings, freight benefits, traffic safety, and CO_2 emissions). We study both systematic and random errors. Data on infrastructure investment CBAs from Sweden and Norway are used to perform the analyses.

Each investment candidate is assumed to have true values of benefits and costs, but the decision maker can only estimate benefits and costs subject to forecasting/measurement errors (which can be systematic or random). The decision maker selects the investments estimated to yield the highest total benefit subject to a budget constraint. This *actual* selection, based on the estimated costs and benefits, is then compared with the *ideal* selection, i.e., the one which would actually yield the highest net benefits and which the decision maker would have selected in the absence of the forecasting/measurement errors. We compare *actual* and *ideal* selections in terms of both the number of investments that are different and the difference in realized benefits, i.e., the loss in net benefits caused by the uncertainty in benefits and costs.

The analysis consists of two parts. In the first, we examine systematic uncertainty in benefit valuations, i.e., the true valuation of a specific benefit is over- or underestimated for all investments. In the second part, we examine random forecasting errors, i.e., when benefits and costs of each project are estimated subject to errors that differ across projects and that may be different for different types of benefits. We use Monte Carlo simulation for this task, with error distributions of investment costs and travel demand based on Flyvbjerg et al.'s studies (2002, 2005), in order to test whether Flyvbjerg's claim "garbage in, garbage out" holds in practice. We also study how fast the quality of CBA recommendations deteriorates as total uncertainty increases. This is similar to an analysis by Eliasson and Fosgerau (2013), but in the present study the representation of uncertainty is more detailed.

Sensitivity of CBA ranking to uncertainty has previously been studied by Börjesson et al. (2014) and Holz-Rau and Scheiner (2011). In both cases it was concluded that CBA ranking is fairly robust against the examined uncertainties. These studies only looked at how the ranking was changed, not at the losses in terms of total net benefits that these changes resulted in, which we do in the present study. We show that this methodological difference is important, as the loss in total net benefits is typically significantly more robust against some types of uncertainty. Essay 3 extends the results in Börjesson et al. (2014) and Eliasson and Fosgerau (2013) in several ways; three different datasets are used and compared; investments are selected under a given budget constraint, rather than selecting a fixed number of objects; uncertainty intervals and probability distributions are based on empirical findings; and more types of uncertainty are explored and compared.

The assumption of a fixed investment can of course be questioned. One could argue that the estimated net present values of potential projects should influence the total size of the investment budget. This may be reasonable in theory, but there is little evidence that it is indeed the case. From this perspective, it seems most realistic to look at ranking and selection decisions under a given budget rather than decisions about the total investment budget.

Our results indicate that selections based on CBA are in fact fairly robust. Selecting investments based on estimated costs and benefits yields much larger total net benefit than random selection from a list of candidates (i.e., disregarding CBA results), even for very high levels of uncertainty. Comparing with a random selection may seem unfair; one might reasonably expect that even if decision makers do not use or trust formal CBAs, there should at least be some correlation between benefits, costs, and decisions. However, this is in fact not the case. Several previous studies have found no or very limited correlation between decisions and measurable benefits and costs (Eliasson et al., 2015; Fridstrøm & Elvik, 1997; Nyborg, 1998; Odeck, 1996, 2010). In other words, it is in fact not uncommon that investment selections are indistinguishable from random selection, from a CBA point of view. Hence, random selection serves as a useful benchmark for assessing the potential gains in total benefit of using CBA.

2.4 Essay 4

Household Production and the Elasticity of Marginal Utility of Consumption

The link between individuals' consumption and wellbeing is at the core of economic analysis, from both a positive and a normative perspective. One way to estimate this relationship is to study the tradeoffs people make between leisure and consumption. Here I suggest an approach that adds household production in this analysis.

The elasticity of marginal utility of consumption (EMUC) is a means for measuring how utility changes with consumption and is of great importance for understanding consumer behavior as well as for policy evaluation. In for instance evaluation of climate change policies, EMUC is one of the most influential parameters in the calculation of the social cost of carbon (Anthoff et al., 2009). Using the Ramsey equation, discounting the costs of future disasters should accounts for both the pure rate of time preference and the growth rate of consumption over time; the two components are added after weighting future consumption with EMUC (see, e.g., Baum, 2009). This weight can also be interpreted as the relative significance of consumption of current vs. future generations, i.e., a distributional interpretation of the concept. In analyses of issues related to risk, the EMUC coefficient corresponds to a commonly used interpretation of the coefficient of relative risk aversion. In a review of empirical studies of EMUC estimates, Evans (2005) reports estimates that are mostly in the range of 1–2.

While previous analyses used the pattern of savings or information about, e.g., the demand for food for approximating EMUC, Ray Chetty (2006) demonstrated that observations of how working time responds to wage changes could be an alternative approach. He argued that if people increase their working time as their wage increases, this implies that on average EMUC is less than unity. Through the Slutsky decomposition of labor supply, there are two effects of wage changes on the demand for leisure: one income effect, where a higher wage increases income and leads to higher demand for leisure, and one substitution effect, which increases the relative price of leisure at the margin and hence reduces the leisure demand. If utility from leisure is also independent of consumption and if market work constitutes the only source of income, an EMUC value equal to unity means that these two effects cancel each other out. If instead EMUC is less than unity, the substitution effect dominates (leisure demand decreases), but if EMUC is greater than unity, the income effect dominates (leisure demand increases). Assuming that reductions (increases) in leisure demand are realized through working time increases (reductions), EMUC can be estimated from evidence on working time responses to wage changes.

The starting point of Chetty's approach is that the (uncompensated) labor supply elasticity with respect to wage is positive on average and hence the average EMUC is lower than unity. If, in addition to wage income, there is unearned income and if consumption and labor are complementary, this upper bound is relaxed. He derived EMUC formulas under such circumstances and computed corresponding numerical values based on labor supply elasticity estimates, and concluded that the existing empirical evidence implies that EMUC must be less than 2: "The intuition for this tight bound is simple: if the marginal utility of wealth diminishes rapidly, why don't people choose to work much less when their wages rise?" (Chetty, 2006, p. 1830).

In Essay 4, I propose an approach to estimate EMUC that is based on an additional basic feature of people's day-to-day tradeoffs made as a result of wage level changes. The idea is that individuals may respond to wage increases not only via adjustment of their labor supply but also by reducing the time spent on housework or other forms of unpaid work. For example, high-wage individuals can reduce time spent in household production by buying services from low-wage individuals. I argue that effective leisure time, rather than time not spent on paid work in the formal sector, is what is relevant when making inferences about the utility function.

The main aim of Essay 4 is therefore to investigate how considerations of household production influence theoretical and empirical conclusions regarding feasible long-term, average values of EMUC. The analysis is restricted to the use of intensive margin responses of labor supply, and I will not explicitly model intertemporal substitution of individuals.

To this end, I develop a model with household production that is used to derive some properties of the bias invoked by the omission of household production. I further derive EMUC equations for two special cases based on the wage elasticity of labor supply. One of these equations can also be used to estimate a lower bound for EMUC under more general conditions.

I use the uncompensated wage elasticity of labor supply rather than – as in Chetty's final expression – the compensated wage elasticity in combination with the income elasticity of labor supply. EMUC estimates from this new specification are less sensitive to the magnitude of the assumed proportion of unearned income to earned income than in the previous formulation. In addition, this specification allows utilization of labor supply elasticity estimates based on other empirical sources, notably time series and cross-country data on mean working times and mean wages, for which it is possible to control for household production to some extent.

The main conclusion of the analysis is that when household production and market work can be substituted, omission of household production in an EMUC equation will generally result in biased estimates. Examples of this are shown in a sensitivity analysis of the differences in results with and without household production. In addition, the sensitivity analysis shows that the results in Chetty (2006) are highly sensitive to the assumed proportion of unearned income to earned income. The main results of the present study suggest a lower bound of the average EMUC close to unity (about 0.9 at the lowest). In addition, I compute point estimates in the range of 0.9–1.6, but unfortunately these latter results should be considered more as an illustration of the proposed method than a final conclusion, since some of the underlying assumptions are based on estimates from a single old, and possibly biased, data source.

3 Comments on policy and future research

From Essay 1, there is one direct policy recommendation, i.e., that global warming potentials cannot be used to calculate the social cost of other climate gases, and this may be especially important when it comes to short-lived GHGs. Instead, social cost estimates from IAMs should be used. From Essay 2, the policy recommendation is not to use $SCCO_2$ estimates from the base case specifications, which are denoted no equity weights in the FUND model (see Waldhoff et al., 2014), since this specification in practice implies regressive income weighting. Instead it is recommended that only equity-weighted estimates be used from the FUND model. Essay 3 shows that although reductions of uncertainty in infrastructure investment CBAs lead to modest gains as share of budget, these shares add up to large total numbers, since national infrastructure budgets are typically large. It is also shown, in line with previous literature, that the greatest potential to increase the quality infrastructure investment decisions may exist in using CBA ranking more consistently. In Essay 4, I show that EMUC should be higher than indicated in a previous study, i.e., Chetty (2006). This may have important consequences for the appropriate way to trade off current and future consumption, as a higher EMUC value implicates a higher discount rate as well as an increased impact of risk aversion and equity weighting when applicable.

Weitzman (2009) argued that climate change mitigation is not primarily about avoiding modest, certain damages, but an insurance strategy against highly uncertain but possible catastrophes. Higher EMUC values strengthen that argument. The reason is twofold. One is that, if EMUC is part of the social risk aversion, the present study strengths the credibility of high estimates of social risk aversion. Increased social risk aversion in turn means that the present value of damages in a low probability, high impact scenario is increased, ceteris paribus. At the same time, a higher EMUC value means that the discount rate in conventional high probability, low impact scenario (where growth is assumed to be positive) is decreased. This means that that the present value of damages in such a high probability scenario decreases as the EMUC increases. In particular, one crucial requirement in Weitzman's model is that EMUC is larger than unity, which closely corresponds to the lower bound estimates in the present study. From this perspective the lower bound of EMUC is an important finding.

Let us now turn to the implication of the present compilation dissertation on the need for future research. In Essay 1, I note that global warming potentials of sulfur hexafluoride sometimes behave in the opposite direction from what is expected when temporal parameters are varied. This phenomenon occurs both in Essay 1 and in Waldhoff et al. (2014), and hence calls for further investigation in future research.

In Essay 2, I consider the proposed approach to adequately solve the identified inconsistency problem, and thus the need for further research on this topic is limited. On the other hand, there may be other methods that work as well and it is possible that the results can be even more generalized to hold in more situations. For example, an even more explicit method would be to use normalized utility functions directly in the CBAs instead of using weights on marginal incomes. With marginal changes, however, this would yield the same answer as the *Ideal* approach suggested in Essay 2. In any case, there will be a need for a continued broader discussion about equity and about how to use distributional weights in light of climate change.

For Essay 3, replication studies using data from additional, preferably non-Scandinavian, countries are ultimately desired. In addition, analyses could be made even more accurate if empirical probability distributions were available for all variables.

In Essay 4, one difficulty in estimating EMUC using the models developed in the present study was to find unbiased estimates of the uncompensated labor supply elasticity with respect to wage. In order to obtain reliable point estimates of EMUC from the proposed formulas, new research with the aim to study the effect of wages on total work supply, rather than the effect of taxes on individual labor supply, is ultimately needed.

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Appendix: Essays 1-4

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