

**ECONOMICS OF CLIMATE CHANGE:
SENSITIVITY ANALYSIS OF SOCIAL COST OF
CARBON**

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ABSTRACT

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Title Economics of Climate Change: Sensitivity Analysis of Social Cost of Carbon	
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Abstract <p>Social cost of carbon (SCC) is the key concept in the economics of climate change. It measures the economic cost of climate impacts. SCC has influence on how beneficial it is to prevent climate change: if the value of SCC increases, investments to low-carbon technology become more attractive and profitable.</p> <p>This paper examines the sensitivity of two important assumptions that affect to SCC: the choice of a discount rate and time horizon. Using the integrated assessment model, we calculate SCC estimates with multiple discount rates and various time horizon lengths.</p> <p>Our results show that discount rate and time horizon have great effect on SCC. For example, the SCC estimates are drastically reduced under the use of a 10% discount rate versus 1% discount rate. Or, when dropping the end year of time horizon from 2300 to 2150, the SCC values decrease by average 12.8% per year. We conclude that if choosing different values of discount rate or time horizon, the outcome of the integrated assessment models can vary greatly.</p>	
Keywords Social cost of carbon, climate change, discount rate, time horizon, integrated assessment models	
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1 INTRODUCTION

Climate change can be considered as the mother of all externalities. It is larger, more complex and more uncertain than any other environmental problem. The source of greenhouse gas (GHG) emissions are diverse. For example, every farm, factory and household emits some GHGs. The effects are similarly diverse: weather affects agriculture, energy use, health and many aspects in nature that in turn affects everything and everyone.

Climate change is also a long term problem. It has been studied that GHGs can stay on atmosphere tens of thousands of years. Even if emissions would be stopped today, many aspects of climate change associated impacts will continue for centuries. However, the quantities of emissions today are enormous. For example, carbon dioxide emissions alone were 24 billion metric tons in 2000 (Tol, 2009).

Key concept in the economics of climate change is the social cost of carbon (SCC). SCC is the total cost to society arising from man-made emissions of carbon dioxide and other GHGs. It is typically measured in U.S. dollars per metric ton of carbon dioxide. SCC is an important concept when analysing the economic impacts of climate change and climate policies.

SCC has significant influence on how beneficial it is to prevent climate change. For example, if the value of SCC increases, investments to low-carbon technology become more attractive and profitable. This can increase the demand of low-carbon technology and enlarge their potential markets. Finnish Minister of Agriculture and the Environment, Kimmo Tiilikainen, has recently emphasized that climate change can be seen as a great possibility for Finnish clean technology companies to create new business (Saavalainen, 2015).

However, like many aspects of climate change, there is a large uncertainty about the social cost of carbon. Estimating the value for SCC is challenging because it is based on integrated assessment models that are extremely sensitive to various assumptions incorporated within the models.

This paper examines the sensitivity of two important assumptions that affect to SCC: the choice of a *discount rate* and *time horizon*. Our analysis is accomplished by calculating SCC estimates with multiple discount rates and various time horizon lengths. As a benchmark study we use United States Government Inter-agency Working Group's (IWG) estimates that are currently the best-known and most widely used SCC estimates. U.S. agencies utilize them to value the benefits of CO₂ emission reductions in federal rulemaking. Our integrated assessment model is calibrated similarly than the models used by IWG.

The rest of the paper is organized as follows. Section 1.1 reviews the previous research related to SCC estimation. Chapter 2 contains theoretical framework including overview of climate change, description of SCC definition, usage and estimation. In Chapter 3, we present the model and its calibration that are used in our SCC sensitivity analysis. Chapter 4 contains the results of our analysis. In Chapter 5, we discuss of the results. Chapter 6 conclude the findings of this paper.

1.1 Previous research

The number of published studies that have attempted to value SCC has increased during the last twenty years. The earliest published estimate of the costs and benefits of carbon emissions is a 1977 paper by Yale University economist William Nordhaus (1977). Nordhaus estimated “shadow prices” for carbon dioxide at 20-year intervals from 1980 to 2160 for different emission scenarios. In the most stringent scenario, the shadow price of carbon in year 2020 is \$109 (in 1977 dollars).

In 2006, British government published a study known as Stern Review (2006). It is considered to be most widely known and discussed report of climate change economics. The main message of the Stern Review is that the benefits of strong, early action on climate change outweigh the costs of not acting. Stern Review calculated mean estimate of SCC of \$85 per tonne of carbon.

Hope (2006) estimated the mean SCC \$19 per tonne of carbon. Interestingly, this is lower if compared to Stern Review even though the both studies are based on the same model, PAGE. However, the Stern team developed a high climate sensitivity scenario reflecting the risk that increasing concentrations of GHGs may be changing the climate more rapidly than was previously believed. This produced damages about 40 percent greater than the comparable basic estimates.

U.S. government IWG (2010) report contain three time series of SCC average values across models, one for each discount rate, increasing over time. For example, in 2015, SCC is valued at \$5, \$23 and \$38 per tonne CO₂. However, since being published, research community has widely criticised that SCC estimates created by IWG are too low. Some researchers have argued that the real value of SCC can be over ten times higher than those presented in the IWG report.

Johnson et al. (2012) re-calculate IWG's SCC estimates using discount rates that weigh future generations' costs and benefits more heavily than those used by the Working Group. For example, with discount rates of 1%, 1.5% and 2%, SCC is valued at \$266, \$122 and \$62 per tonne CO₂.

Nordhaus (2014) estimated SCC using the latest version of DICE (a model developed by himself). His estimate is \$18.6 per carbon tonne in 2015, increasing 3% per year over the period to 2050. It is noteworthy that the DICE model results are

lower than the estimates of PAGE model, which was used in e.g. Stern Review. This is mainly caused by differences in the choice of discount rate. As a consequence, Nordhaus emphasizes that the major issues concerning the SCC include the selection of appropriate discount rate.

Dayaratna et al. (2013) reckons that time horizon affects strongly to SCC. In their study, the outcome differs significantly when changing the end year of time horizon. For example, in 2015, SCC will drop 48.1% as a result of changing end year from 2300 to 2150.

2 THEORETICAL BACKGROUND

This chapter provides insight in the economic theories that are relevant for the problem of climate change. First an overview of the changing climate itself, how it is caused and its future impacts is given. Second, the concept of social cost of carbon is presented in more detail. Third part of this chapter describes how social cost of carbon can be estimated and discusses discounting and the treatment of uncertainty.

2.1 Climate Change

Observed Changes and Their Causes

Warming of climate system is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Each of the last three decades has been successively warmer than any preceding decade since 1850. (Cubasch et al., 2013.)

During the last twenty years, the Greenland and Antarctic ice sheets have been losing mass with increasing rate. Mountain glaciers have continued to shrink while northern hemisphere spring snow has been decreasing constantly. Also, there are numerous long-term changes observed in other aspects of climate change. For example, there are changes in global rainfall patterns and an increase in the frequency and intensity of extreme weather events such as heat waves, heavy rain falls and tropical cyclones. (IPCC, 2007.)

GHGs that are largely driven by economic and population growth, have increased since pre-industrial era and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are record-high in the last 800,000 years. This alters the energy balance in atmosphere which is expressed as an increase or decrease in radiative forcing. An increase in radiative forcing translates eventually into a rise in temperature. (IPCC, 2014.)

The GHGs that have the largest impact on radiative forcing are carbon dioxide, methane and nitrous oxide. They are called long-lived GHGs because they can stay in the atmosphere centuries. Among these GHGs, CO₂ is the largest contributor of the concentrations in the atmosphere and are primarily caused by the use of fossil fuels and, to a lesser extent, by deforestation. The problem of climate change emerges only when there are more emissions than can be removed from the atmosphere. This increases concentrations, radiative forcing and eventually temperature.

Despite a growing number of climate change mitigation policies, total GHG emissions have increased constantly over 1970 to 2010. About 40% of these emissions

have remained in the atmosphere. The rest have been removed from the atmosphere and stored on land (in plants and soils) and in the ocean. This has caused, for example, ocean acidification. (IPCC, 2014.)

Projected Changes in Climate system and Future Risks

IPCC (2014) forecasts various scenarios for global warming depending on cumulative CO₂ emissions. In the most optimistic scenario, that would require substantial emissions reductions over next decades and near zero emissions of CO₂ by the end of century, it could be possible to keep global warming 2°C above pre-industrial temperatures. However, implementing such reductions would be a technological and economical challenge that would require significant financial investments.

If we continue “business as usual”, without additional efforts to reduce emissions, emissions growth is expected to continue due to growth in global population and economic activities. In this scenario the increase of global mean surface temperature is likely to range from 3.7°C to 4.8°C above pre-industrial temperatures. (IPCC, 2014.)

Because of warming, the ability of land and oceans to absorb CO₂ decreases as temperature rises. As a result, higher fraction of GHG emissions stay in the atmospheres. This is called “positive carbon cycle feedback” and it amplifies climate change. (IPCC, 2007.)

There is a wide range of future risks related to climate change. They include, for example, more frequent hazardous extreme events and increasing vulnerability and exposure of human and natural systems. IPCC (2014) estimates that rising rate of global warming, ocean acidification and other changes in climate system will increase the risk of severe, irreversible impacts on ecosystems.

Many animal and plant species are facing increasing risk of extinction due to climate change. For example, most plant species cannot naturally shift their geographical location fast enough to keep up with rising temperature. Marine organs, such as coral reefs, are highly vulnerable due to lower oxygen levels and higher ocean acidification. (IPCC, 2014.)

Food and agricultural sectors are expected to suffer a lot from climate change. As local temperature rises crop yields are likely to rise at higher latitudes. However, crop yields at lower latitudes are likely to decrease which dampen the economy and raises the risk of hunger. Furthermore, renewable surface water and groundwater resources are likely to reduce in most dry subtropical regions that could intensify competition for water. (IPCC, 2014.)

From poverty perspective climate impacts will likely slow down economic growth that makes the poverty reduction more difficult, especially in developing countries with low income. When this is combined with increased competition for water and suffering food production, the risk of violent conflicts increases.

Gleick (2014) argues that water and climatic conditions have played a significant role in Syria's uprising. Starting in 2006 and lasting through 2011, Syria suffered the worst long-term drought and the most severe crop yield failures in history. The decrease in water availability, water mismanagement, agricultural failures, and related economic deterioration have led to population dislocations and the migration of rural communities to nearby cities. These factors have contributed to unemployment, economic problems and food insecurity for more than a million people, causing social unrest.

In the next section, climate change is described in economic context as market failure.

2.2 Climate Change as Market Failure

Climate can be seen as a public good, because it has the characteristics of non-rival and non-excludable. Being non-rival means everyone can enjoy climate without reducing the available consumption opportunities for others. Being non-excludable means it is impossible to effectively exclude someone from enjoying the climate. (Sandler, 2004.)

Climate change can be seen as market failure that is caused by global GHG emissions (Stern, 2006). Global GHG emissions are negative externalities because the costs of them are mainly paid by future generations, not by the polluters. Therefore, polluters have no or little incentive to reduce the emissions as they do not directly face the full costs they cause on society. This is illustrated in Figure 2-1. Social costs of the current level of GHG emissions (Q2) are higher than the private costs at the equilibrium. Optimal level of GHG emissions (Q1) would be at the intersection of social cost curve and demand curve.

In order to overcome this type of externality, one solution is to set a price on emissions that equal to social costs. This can be done using Pigouvian tax or by establishing property rights to pollutions through cap and trade systems. However, whether a price on emissions is set by a tax or through a cap and trade system, optimal policy design requires knowing the monetized social marginal costs from GHG emissions. In the case of CO₂ emissions, this marginal monetized externality value is known as the social cost of carbon. (Metcalf & Stock, 2015a.)

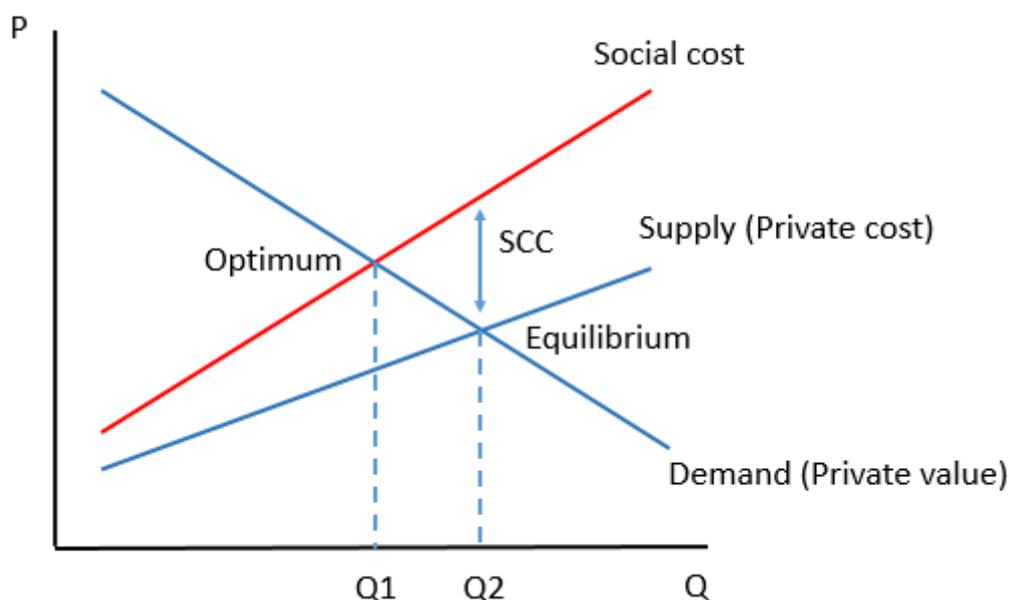


Figure 2-1. Climate change as market failure.

2.3 Social Cost of Carbon

SCC presents the economic cost of climate impacts. More precisely, it can be defined as the additional economic harm caused by one additional metric ton of CO₂ emissions (Ackerman & Stanton, 2012). In Figure 2-1, SCC is illustrated as the difference between social costs and private costs. Most often SCC is expressed in U.S. dollars per one carbon ton.

As mentioned in previous section, SCC can be used in defining climate policies. For example, in case of carbon tax, the price per carbon ton can be applied as a tax on fuels. In government regulation, SCC can be applied when banning the polluting technology. This kind of regulation can be based on cost-benefit analysis: agencies use SCC to measure the monetary benefits of regulations that reduce carbon emissions and weigh them against the costs of the regulation. (Ackerman & Stanton, 2010.)

As mentioned in Chapter 1, in 2010 the United States Government developed SCC estimates to value the benefits of CO₂ emission reductions in federal rule-making. U.S. agencies are now required to apply the SCC to assess the potential benefits of CO₂ reductions in federal regulations, including rules and proposals affecting appliances, transportation, industry, and power generation (IWG, 2010). Calculation of U.S. SCC estimates is described in more detail in Section 3.2.

In addition to public sector, also many companies use SCC, but in different way. According to Carbon Disclosure Project (2013) companies use carbon price as a planning tool to help identifying revenue opportunities, risks, and as an incentive

maximise energy efficiencies to reduce costs and guide capital investment decisions.

Estimating the value for SCC can be highly challenging. Researchers have used integrated assessment models to explore the pathways through which GHG emissions contribute to climate change and assess economics impacts of them. This is discussed in the next section in more detail.

2.4 Estimating Social Cost of Carbon

Integrated assessment models (IAMs), that are used to estimate SCC, combine scientific and socio-economic aspects of climate change. IAMs track emissions, the concentration of GHGs in the atmosphere as well as carbon sinks, temperature and other climate impacts arising from concentrations of GHGs in atmosphere, and converts those to monetary damages. (Metcalf & Stock, 2015b.)

A combined model is required because there is continuous interaction between economy, welfare and climate system (Figure 2-2). For example, emissions affect to climate change through atmospheric concentrations and radiative forcing. Climate change effects on economic production and welfare. And, on the other hand, economic production and welfare affect to emissions. A policy that changes one of the above-mentioned aspects changes all the aspects and their influence on each other over time. Also, such as positive carbon cycle feedbacks can amplify the climate change further depending on the level of warming. (Mastrandrea, 2010.)

Currently the most widely used IAMs in SCC estimations are DICE (Nordhaus, 2008), FUND (Anthoff & Tol, 2013) and PAGE (Hope, 2013). In these models, the main input parameters include the future path of emissions, economic growth, population growth, climate sensitivity and discount rate. However, each model takes slightly different approach of how changes in emissions result in changes in economic damages. The differences between the DICE, FUND and PAGE models are discussed in Johnson et al. (2012) and Diaz (2014). The DICE model is described in more detail in Section 3.1.

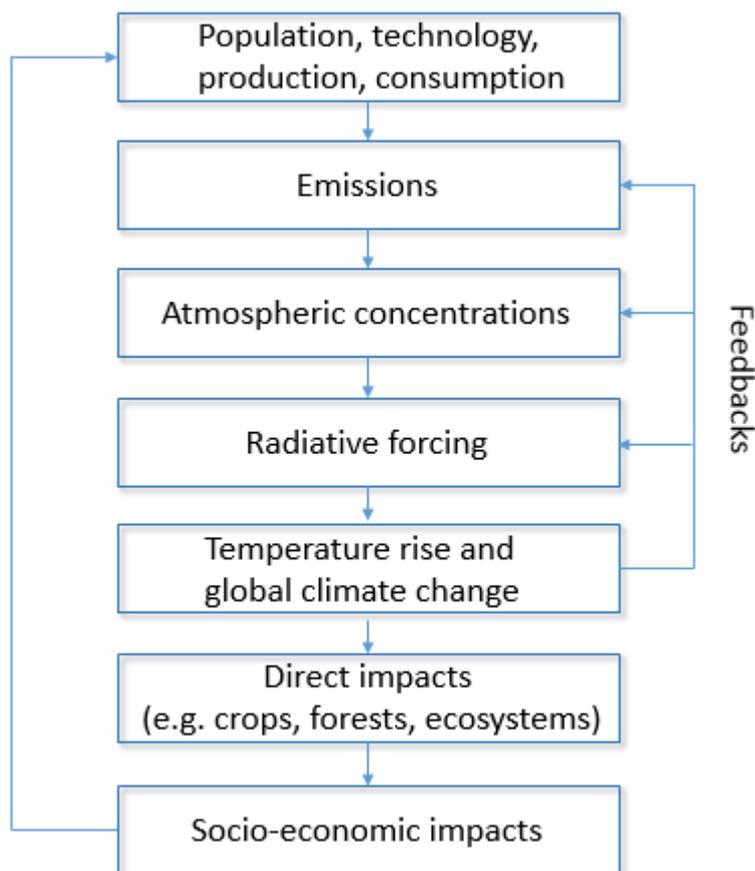


Figure 2-2. The process in estimating social cost of carbon.

Estimations are run using Monte Carlo framework and they span typically over hundreds of years, i.e. starting in 2000 and continuing until 2300. Like many aspects of climate change, there is also a large uncertainty about the social cost of carbon. In the next section we will discuss uncertainties that affect to SCC calculation.

2.4.1 Treatment of Uncertainty

IAMs of all types must make choices about how to account for critical uncertainties in climate and socio-economic systems and their interactions. Different assumptions about these parameters can create significantly different outcomes.

Some parameters have great influence on short run whereas other parameters are important in long run. Some parameters are known quite well while others are not. There are also ethical values, such as discount rate which determines how we value the welfare of future, unborn generations. However, some parameters, such as climate sensitivity, are important consistently. (Anthoff, 2013.)

Climate sensitivity is the long-term temperature increase expected from a doubling of the concentration of carbon dioxide in the atmosphere. It measures the pace of global warming. For example, Roe & Baker (2007) point out that feed-

backs in climate system can have significant effect on climate sensitivity. The amplitude and frequency of feedbacks are estimated to increase with temperature. Although the effect of a single feedback mechanism to climate sensitivity can be linear, but multiple feedbacks occurring simultaneously can have nonlinear, quadratic effect.

Ackerman & Stanton (2012) describe how climate sensitivity, and other uncertain parameters, can be treated using probability distribution within IAMs. For example in DICE, during Monte Carlo analysis, the value of climate sensitivity is repeatedly selected from its probability distribution

2.4.2 Discount Rates

Estimates of the SCC combine the present and future damages together as one value, the total monetized impact of an additional ton of CO₂. Discounting is needed to combine the costs from different time periods together. However, farther into the future that costs take place, the less these costs will matter in today's decision making.

When discounting is used to combine values from a short span of years, a market rate of interest is often considered as appropriate discount rate (e.g. 3%). However, when discounting takes place across a longer span of time, the logic of using market rates becomes troubled. There is no simple logic to compare mitigation costs incurred today while their greatest benefits will be achieved after a century or more into the future. (Ackerman & Stanton, 2010.)

Ackerman & Stanton (2010) point out that the choice of a discount rate is also an ethical judgment, not a data point that can be found in the financial pages. The higher the discount rate that is chosen, the less future costs are valued at present-day. However, lower discount rates or even a zero discount rate can be used to show that our society takes seriously the costs to be suffered by future generations.

Pindyk (2015) highlights that the problem is that while we don't have appropriate framework for identifying discount rates for longer time periods, different rates will yield wildly different estimates of the SCC. As mentioned in Section 1.1, difference in discount rate largely explains why the IAM based analyses of Nordhaus (2014) and Stern (2006) result such diverse SCC estimates.

The choice of discount rate is discussed in more detail in e.g. Goulder and Williams (2012). In the next chapter, we examine the sensitivity of SCC with respect to discount rate and time horizon.

3 MODEL AND CALIBRATION

In our sensitivity analysis, we will calculate SCC estimations using DICE model (one of the models used by IWG) with multiple discount rates and various time horizon lengths. The calibration of DICE will follow similar choices than in IWG (2010). In the following sections, we will describe the DICE model and calibration in more detail.

3.1 DICE model

DICE, the Dynamic Integrated Climate and Economy model was developed by William Nordhaus. DICE is based on the Solow-Swan growth model. Economic output is modeled using a Cobb-Douglas production function:

$$Y_t = A_t N_t^{1-\alpha} K_t^\alpha$$

where Y_t is total output, K_t is capital, N_t is labor and A_t is total factor productivity. The parameter α (the elasticity of output with respect to capital) is set to 0.3 in DICE. (Moyer et al., 2014.)

A key input, among discount rate and GDP, population and carbon emissions trajectories, is climate sensitivity. Each individual estimate of the SCC is the realization of a Monte Carlo simulation based on a draw from an equilibrium climate sensitivity distribution to model the impact of CO2 emissions on temperature. (Moyer et al., 2014.)

DICE estimates the SCC by first determining the base consumption pathway C_b as climate damages are calculated as lost consumption. Next, it adds a ton of carbon to total emissions in year t and recalculates the consumption pathway after that year, C_1 . The model then finds the difference in the two pathways in each year, applies the appropriate discount rate r , and sums the differences:

$$SCC_t = \sum_{t=\tau}^T \frac{(C_b - C_1)_t}{(1+r)^t}$$

Because the climate sensitivity parameter is modelled probabilistically the output of each model run is a distribution over the SCC in year t . The process is repeated for all time periods T of the defined time horizon. (Moyer et al., 2014.)

In this thesis, we employ a MATLAB implementation¹ of DICE that is based on work by Kopp et al (2012). In the next section, we will describe how the DICE is calibrated in our analysis.

3.2 Calibration

In order to calibrate DICE similarly than by IWG, we need to run the model with the following input parameters:

- A Roe and Baker distribution for the climate sensitivity parameter bounded between 0 and 10 with a median of 3 °C and a cumulative probability between 2 and 4.5 °C of two-thirds;
- Five sets of GDP, population and carbon emissions trajectories based on EMF-22 socio-economic scenarios.

IWG used constant annual discount rates of 2.5, 3, and 5 percent. In our sensitivity analysis, we will utilize wider discount rate range, from 1% to 10%. For climate sensitivity parameter, IWG used Excel-based valuelist of Roe and Baker distribution. However, because the Excel file was not available in public, we replaced it with a MATLAB-based function developed by Kopp (2012) that emulates Roe and Baker distribution.

As socio-economic pathways are closely tied to climate damages, therefore it is typical to model several input parameter trajectories in tandem: GDP, population and carbon emissions. A wide variety of scenarios have been developed and used for climate change policy simulations, including IPCC (2014) and Stanford Energy Modeling Forum, EMF-22 (Clarke & Weyant, 2009).

IWG decided to rely on the scenarios developed by EMF-22. Out of the 10 models included in the EMF-22 exercise, IWG selected the trajectories used by MiniCAM, MESSAGE, IMAGE, and the optimistic scenario from MERGE. These four of the scenarios represent so-called business-as-usual (BAU) growth in population, wealth, and emissions and are associated with CO₂ concentrations ranging from 612 to 889 ppm in 2100. A fifth scenario, the 550 ppm average, represents an emissions pathway that achieves stabilization at 550 ppm CO₂ in 2100, a lower than BAU trajectories. For this scenario, IWG averaged the GDP, population, and emission trajectories of the four EMF-22 based models. (IWG, 2010)

GDP, population and carbon emission projections of the scenarios are presented in Table 1. Also, they can be found in Excel format from the source code. The results of our analysis are presented in the next chapter.

¹ Source code: <https://github.com/storniai/SCC-DICE>

Table 1. Socioeconomic and emissions projections from EMF-22 Reference Scenarios.

GDP (using market exchange rates in trillion 2005\$)						
EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	38,6	53,0	73,5	97,2	156,3	396,6
MERGE Optimistic	36,3	45,9	59,7	76,8	122,7	268,0
MESSAGE	38,1	52,3	69,4	91,4	153,7	334,9
MiniCAM	36,1	47,4	60,8	78,9	125,7	369,5
550 pm average	37,1	49,6	65,6	85,5	137,4	337,9
Global Population (billions)						
EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	6,1	6,9	7,6	8,2	9,0	9,1
MERGE Optimistic	6,0	6,8	7,5	8,2	9,0	9,7
MESSAGE	6,1	6,9	7,7	8,4	9,4	10,4
MiniCAM	6,0	6,8	7,5	8,1	8,8	8,7
550 pm average	6,1	6,8	7,6	8,2	8,7	9,1
Fossil and Industrial CO2 Emissions (GtCO2/yr)						
EMF – 22 Based Scenarios	2000	2010	2020	2030	2050	2100
IMAGE	26,6	31,9	36,9	40,0	45,3	60,1
MERGE Optimistic	24,6	31,5	37,6	45,1	66,5	117,9
MESSAGE	26,8	29,2	37,6	42,1	43,5	42,7
MiniCAM	26,5	31,8	38,0	45,1	57,8	80,5
550 pm average	26,2	31,1	33,2	32,4	20,0	12,8

4 RESULTS

This chapter contains the results of our analysis. In the following sections, we present the effect of discount rate and time horizon on SCC.

4.1 Discount Rate Sensitivity

To explore the effect of discount rate on SCC, we run the DICE model with discount rates from 1% to 10%, ten-year time steps from 2005 to 2300, using five sets of GDP, population and carbon emission trajectories and a Roe and Baker distribution for the climate sensitivity parameter. This produces overall 5000 iterations in Monte Carlo framework. Results are shown in Table 2 where average SCC values of iterations are presented per year and per discount rate for period 2015 – 2065. The results of time horizon of 2005-2300 are included in Appendix 1.

Table 2. Social cost of carbon with discount rates 1%-10% (in 2007 dollars).

Discount rate:	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %	9 %	10 %
Year	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Avg
2015	332,4	101,3	41,5	22,4	12,9	9,0	6,4	4,9	3,9	3,1
2025	366,8	119,9	51,8	28,9	17,2	12,2	8,9	6,9	5,5	4,5
2035	403,2	140,5	63,5	36,6	22,3	16,1	11,9	9,3	7,5	6,2
2045	441,3	163,2	76,8	45,5	28,2	20,6	15,4	12,1	9,9	8,2
2055	480,7	187,7	91,6	55,5	35,0	25,9	19,6	15,5	12,7	10,6

As the results in above table indicate, a higher discount rate results a lower SCC value, and vice versa. For example, in year 2015, SCC vary between 3.1 – 332.4 dollars when discount rate alternates from 10% to 1%. In 2055, the corresponding variation is 10.6 – 480.7 dollars. These results clearly illustrate the great sensitivity discount rate can cause, as the highest SCC value is over 100 times greater than the lowest one is the same year.

For discount rates of 1% and 10%, the average annual growth rates of SCC are 10.3% and 47.7% in 2015 - 2055. Therefore, for a lower discount rate the annual growth rate of SCC is smaller, although the level and magnitude of annual SCC values are higher. The annual growth rates for all ten discount rates are listed in Appendix 2.

Figure 4-1 illustrates how SCC varies per discount rate in one year (2015): the slope decreases more rapidly in 1% - 3% than in 3% - 10%. Figure 4-2 illustrates how SCC develops over time horizon of 2005 – 2300 with multiple discount rates: the slopes show that SCC goes higher with lower discount rates, and vice versa.

Specially, it can be noticed that the slope of 1% discount rate is significantly greater than the any other ones while the slope of 10% is clearly at the bottom. These results indicate that the effect of discount rate on SCC is merely non-linear than linear.

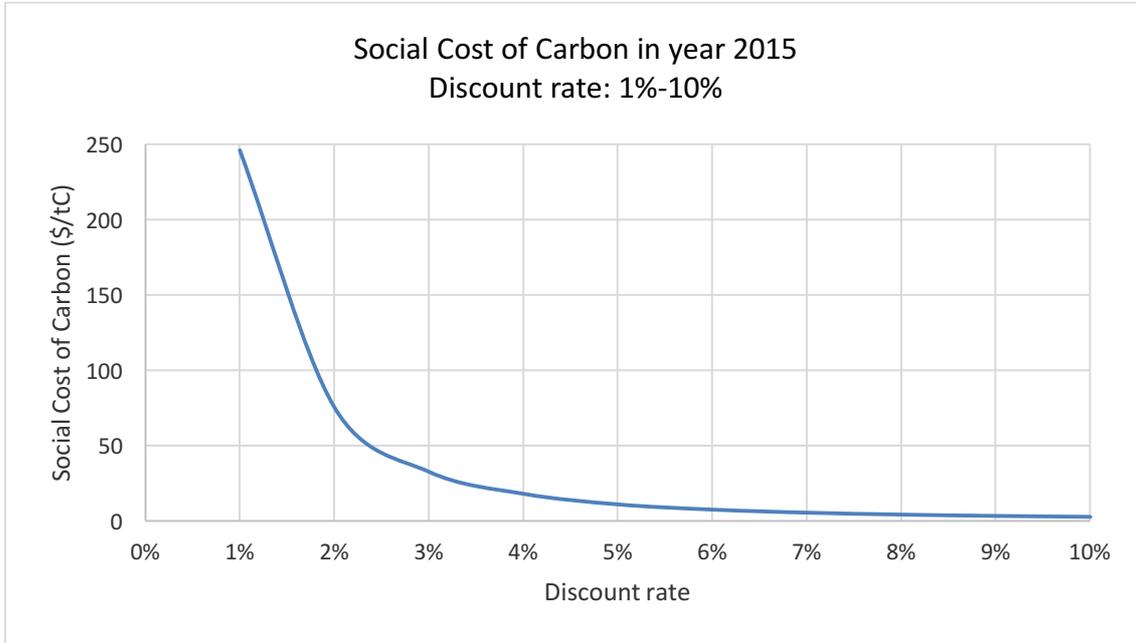


Figure 4-1. SCC in year 2015 with discount rates 1%-10%.

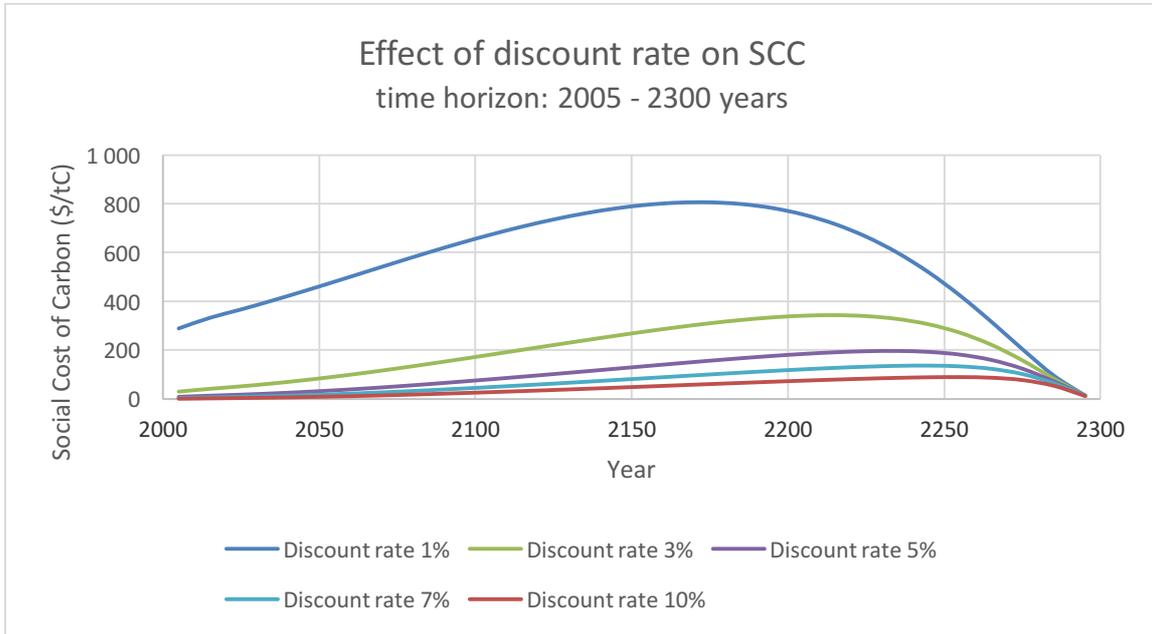


Figure 4-2. SCC in 2005-2300 with discount rates 1%, 3%, 5%, 7% and 10%.

In Figure 4-2, the SCC is rising in the beginning of time horizon and declining towards the end. The shapes of the slopes are based on socio-economic scenarios that are given as input to DICE model. In the beginning, SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change. However, IWG assumed that population and GDP growth rates

decline linearly from 2100 forward, reaching zero in 2200 and 2300, respectively. For this reason, SCC reaches to zero in 2300. More information of the socio-economic scenarios can be found in IWG (2010) and Clarke & Weyant (2009).

Next, we examine how time horizon affects to SCC.

4.2 Time Horizon Sensitivity

To explore the effect of time horizon on SCC, we run the DICE model with different time horizon lengths. First, we run the model in ten-year time steps from 2005 to 2200 with constant discount rate of 3%. After that, we conduct a second run with similar setup, but with shorter time horizon, from 2005 to 2150. Both runs produce overall 5000 iterations per each in Monte Carlo framework. Results are shown in Figure 4-3 where the SCC slopes per end year are presented. Also, the SCC slope with original time horizon from 2005 to 2300 with 3 % discount rate is included, that was calculated in the previous section.

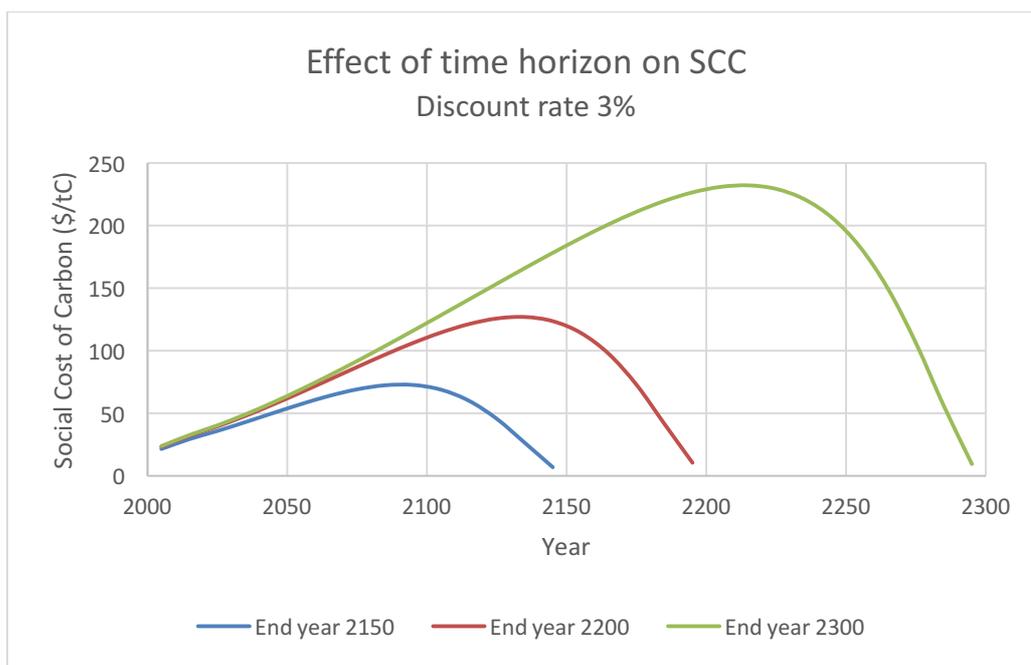


Figure 4-3. Average SCC values with different end years.

As the above figure show, the SCC alternates greatly as a result of changing end year. Reducing the length of time horizon decreases the SCC, and vice versa. For example, if the end year is changed from 2300 to 2200, the SCC values drop by average 2.2% per year in period 2015 – 2055. Or, when changing end year from 2300 to 2150, the SCC values drop by average 12.8% per year in the same period. The full set of annual average SCC percent changes per end year are presented in Table 3.

Table 3. Average SCC percent change as a result of changing end year.

End year:	2150	2200
Year		
2015	-9,7 %	-1,7 %
2025	-10,8 %	-1,9 %
2035	-12,3 %	-2,3 %
2045	-14,2 %	-2,8 %
2055	-16,8 %	-3,4 %
Average:	-12,8 %	-2,4 %

5 ANALYSIS OF THE RESULTS

5.1 Comparison with the Other Studies

As our results indicate, discount rate and time horizon strongly affect to SCC. For example, SCC estimates are drastically reduced under the use of a 10% discount rate versus 1% discount rate. Or, when dropping the end year of time horizon from 2300 to 2150, the SCC values decrease by average 12.8% per year. In the below-shown tables our results are presented with the outcomes of other studies.

Table 4. SCC in year 2015 from different studies (in 2007 dollars).

Discount rate:	1%	2%	2,5%	3%	4%	5%	6%	7%	8%	9%	10%
This paper	246,2	75,5		32,6	17,9	10,9	7,4	5,4	4,1	3,2	2,6
IWG (2010)			38,4	23,8		4,7					
Johnson et al. (2012)	266,0	62,0	35,0	21,0		5,0					
Nordhaus (2014)			58,0	40,2	21,0	12,3					

As we can see in Table 4, the discount rate sensitivity explored in this paper is in line with the results of other studies. When changing the discount rate, the average SCC percent change is approximately in the same level in all studies, when comparison is possible. However, the absolute values of SCC differ slightly. For example, the SCC estimates of IWG (2010) and Johnson et al. (2012) are lower than our results or Nordhaus (2014). The main reason of this is that IWG and Johnson et al. utilized three IAMs (DICE, FUND and PAGE) to determine SCC, giving each model equal weight and summarizing the average values across all models. We and Nordhaus ran the calculations using only one model, DICE.

There are differences between IAMs that cause variation in the results. For example, DICE projects substantially higher climate damages, and therefore higher SCC values, than FUND, which also includes the potential net benefits of climate change in the near future (Diaz, 2014). The variation between our SCC estimates and Nordhaus's ones is mainly caused by different version of DICE model. Nordhaus used updated DICE-2013R while we employed DICE-2007.

Table 5. Average SCC percent change in year 2015 as a result of changing end year.

End year:	2150	2200
This paper	-9,7 %	-1,7 %
Dayaratna et al. (2013)	-48,1 %	

Table 5 contain average SCC percent change in year 2015 as a result of reducing time horizon length. The outcome of our results versus Dayaratna et al. (2013) differs greatly: when changing the end year from 2300 to 2150, Dayaratna et al.

estimated that average SCC will drop 48.1% in year 2015. By contrast, we calculated that the corresponding drop is only 9.7%. The great discrepancy is explained by the difference in climate sensitivity. Dayaratna et al. chose climate sensitivity distribution from Otto et al. (2013) while we utilized Roe and Baker distribution.

The Otto et al. distribution has mean value of 2.0°C with a 5–95% confidence interval of 1.2–3.9°C whereas the corresponding values of the Roe and Baker distribution are 3.5°C and 1.7–7.1°C, respectively. As the 95th percentile value is only 3.9°C, the likelihood of occurrence of high temperature, large impact events are greatly diminished under the Otto et al. distribution. Because of this, the SCC is lower when Otto et al. distribution is used.

5.2 Limitations of the Model

There are several limitations in the DICE model – like in any model that aims to measure the impacts of climate change. For example, the accuracy of the results will drop when time horizon increases. According to Liski (2004), the main reason for this is that the models cannot predict the dynamic changes in economic structure that are driven by climate change over time. It is likely that current production technology will be replaced with new low-carbon technology, while the development of information technology may also provide benefits in the future that are not yet known. However, for example in the DICE model, the current economic structure is projected on the future taking GDP, population and emissions trajectories as exogenous input parameters. Because of this, the positive effect of creation of new technology and new business are not included in SCC estimation.

Also, the fundamental problem in SCC estimation is the uncertainty of many aspects of climate change. Because of this, the models are based on several assumptions that typically reflect the subjective views of the model authors (Liski, 2006). For example, Figure 5-1 illustrates one possible scenario that is based a certain set of assumptions: implementation of Policy A is assumed to bring 70 percent emission reduction that leads to stabilization of CO₂ concentrations at 550 ppm in 2100. This results global warming of 2.0°C that, in turn, can be translated to a certain level of social cost of carbon (SCC_A).



Figure 5-1. Example scenario.

If the above-mentioned chain of events would be well-known, it would be possible to calculate more accurate SCC estimates. However, in reality, each phase in Figure 5-1 can result several different outcomes. For example, it is not sure that a pre-defined emission trajectory, that is given as input to the DICE model, leads

to a certain level of CO₂ concentrations: 70 percent drop of GHG emissions can also lead to stabilization at 450 ppm or 650 ppm with equal probability. Or, it is possible that CO₂ concentration of 550 ppm can result only warming of 1.0°C, but more likely it could lead to warming of 3.0°C or higher. (Liski, 2006.) Therefore, the outcome of the models can vary greatly, depending on the assumptions.

For example, if each phase of the scenario shown in Figure 5-1 would contain three different outcomes with equal probability, this can lead to 27 combinations of SCC estimates (Figure 5-2). This makes evaluation of SCC and climate policies more challenging. In the next section, we discuss climate policy under uncertainty.

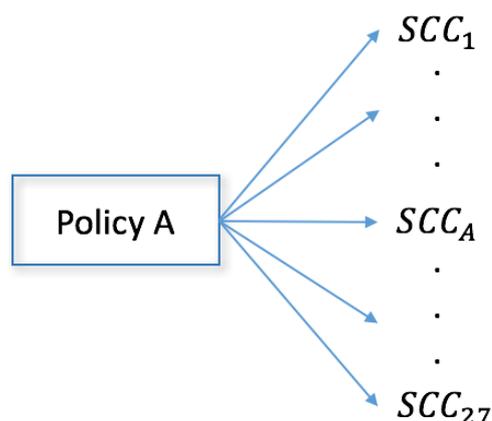


Figure 5-2. A policy can lead to multiple SCC combinations.

5.3 Climate Policy Under Uncertainty

The discount rate and time horizon sensitivity combined with the limitations of the models can result wide range of SCC estimates. Depending on the choices, the model outcomes can indicate that climate change is serious problem and will have significant impact on our economy, or, on the other hand, that it is not a problem at all. Because of this, the decision making of climate policies can be challenging. For example, it can be difficult to justify strict emission reductions if the nature of SCC estimates is highly speculative.

Liski (2006) argues that climate policies cannot be evaluated by only listing the costs and benefits and calculating the difference. He emphasizes that more information of the involved risks is needed to support the decision making. Climate policies can be profitable even if the costs are higher than the benefits, if the risk of the catastrophic events is reduced or prevented. According to Liski, this kind of “climate insurance” approach would be more suitable as the decision makers are typically keen to avoid risks. This would be an interesting area for further research.

In the next chapter, we conclude the findings of this paper.

6 CONCLUSIONS

The research objective of this thesis was to examine the sensitivity of two important assumptions that affect to SCC: the choice of a discount rate and time horizon. Our analysis is accomplished by calculating SCC estimates with multiple discount rates and various time horizon lengths. The calculations are done using the DICE model, one of the models used by IWG. For this purpose, we implemented a MATLAB-based version of DICE incorporated with e.g. Monte Carlo framework to simulate Roe and Baker distribution as climate sensitivity.

Our results clearly show that discount rate and time horizon have strong effect on SCC. For example, SCC estimates are drastically reduced under the use of a 10% discount rate versus 1% discount rate. Or, when dropping the end year of time horizon from 2300 to 2150, the SCC values decrease by average 12.8% per year. These outcomes are in line the results of other studies, when comparison is applicable.

The SCC is based on the integrated assessment models that are extremely sensitive to various assumptions incorporated within the models. Choosing distinct values of discount rate or time horizon, the outcome of the models may differ greatly. Since the moderate and defensible changes in assumptions can lead to large changes in SCC estimates, the results may not be reliable enough to justify trillions of euros' government policies.

6.1 Further Research

In this thesis, we calculated the SCC estimates using constant discount rate for entire time horizon. However, it would be more realistic to utilize a discount rate scheme that varies over time, as the real market rates do. Specially, it would be interesting to explore the effect of negative discount rates on SCC, as e.g. the current deposit rate of European Central Bank is historical low of -0.4 percent.

As mentioned in Chapter 1, the sources and impacts of GHG emissions are diverse. The industrial economies emit the most of the GHGs while those in low-income countries that contribute least to climate change are most vulnerable to its effects. If the same constant discount rate is utilized for the both industrial and poor countries, then the future costs of climate change are not weighted equally. For example, a cost of \$100 per person has much higher impact for African countries than United States. This might not provide enough incentive for industrial economies to reduce GHG emissions. Therefore, SCC could be calculated per country basis with adjusted discounting: the countries that emit more GHGs should be treated with lower discount rates that results higher SCC.

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APPENDIX 1

Table 6. Social cost of carbon, 2005-2295 (in 2007 dollars).

Discount rate:	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %	9 %	10 %
Year	Avg	Avg								
2005	289,0	80,1	30,2	15,1	8,2	5,4	3,7	2,7	2,0	1,6
2015	332,4	101,3	41,5	22,4	12,9	9,0	6,4	4,9	3,9	3,1
2025	366,8	119,9	51,8	28,9	17,2	12,2	8,9	6,9	5,5	4,5
2035	403,2	140,5	63,5	36,6	22,3	16,1	11,9	9,3	7,5	6,2
2045	441,3	163,2	76,8	45,5	28,2	20,6	15,4	12,1	9,9	8,2
2055	480,7	187,7	91,6	55,5	35,0	25,9	19,6	15,5	12,7	10,6
2065	520,8	213,8	107,7	66,7	42,8	32,0	24,3	19,4	16,0	13,4
2075	560,9	241,1	125,1	78,9	51,3	38,7	29,7	23,8	19,7	16,6
2085	600,2	269,2	143,5	92,0	60,6	46,1	35,6	28,7	23,8	20,2
2095	637,9	297,6	162,5	105,8	70,5	54,0	41,9	33,9	28,3	24,0
2105	673,2	325,8	181,8	119,9	80,7	62,2	48,5	39,5	33,0	28,1
2115	705,7	353,5	201,3	134,3	91,2	70,6	55,4	45,2	37,9	32,3
2125	734,8	380,3	220,9	149,0	102,0	79,4	62,4	51,1	43,0	36,7
2135	759,8	405,9	240,2	163,7	113,0	88,3	69,7	57,2	48,2	41,3
2145	780,2	429,8	259,1	178,5	124,1	97,4	77,1	63,5	53,6	45,9
2155	795,0	451,5	277,3	193,0	135,2	106,5	84,6	69,8	59,0	50,7
2165	803,5	470,4	294,4	207,1	146,3	115,6	92,2	76,2	64,5	55,5
2175	804,8	485,6	310,0	220,5	157,0	124,5	99,6	82,6	70,0	60,3
2185	797,8	496,4	323,4	232,8	167,2	133,2	106,9	88,8	75,5	65,1
2195	781,3	501,7	334,0	243,6	176,6	141,4	113,9	94,9	80,7	69,7
2205	754,4	500,3	340,9	252,3	184,9	148,8	120,4	100,6	85,7	74,2
2215	715,6	490,9	343,1	258,1	191,6	155,2	126,2	105,8	90,4	78,3
2225	664,0	472,0	339,1	260,1	196,0	160,1	131,0	110,3	94,5	82,0
2235	598,3	441,6	327,3	256,8	197,1	162,8	134,4	113,8	97,9	85,2
2245	517,9	398,1	305,5	246,1	193,2	162,0	135,4	115,6	100,1	87,5
2255	423,2	339,7	271,1	225,3	181,9	155,7	132,3	114,5	100,1	88,3
2265	316,5	266,2	221,9	191,3	160,0	140,6	122,3	108,0	95,9	85,7
2275	203,5	180,0	157,6	141,8	123,7	112,4	101,0	91,7	83,5	76,3
2285	96,0	89,7	82,8	78,2	71,7	68,0	63,7	60,1	56,7	53,5
2295	14,5	14,3	14,0	13,9	13,5	13,4	13,2	13,0	12,9	12,7

APPENDIX 2

Table 7. Changes in the Average Annual Growth Rates of SCC Estimates between 2015 and 2065.

Discount rate:	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %	9 %	10 %
Year										
2015	15,0 %	26,3 %	37,1 %	47,2 %	56,6 %	65,6 %	74,3 %	82,6 %	90,7 %	98,5 %
2025	9,9 %	17,8 %	23,8 %	28,5 %	32,2 %	35,2 %	37,6 %	39,6 %	41,2 %	42,6 %
2035	9,5 %	16,5 %	21,7 %	25,6 %	28,7 %	31,1 %	33,1 %	34,7 %	36,1 %	37,2 %
2045	8,9 %	15,2 %	19,7 %	22,9 %	25,4 %	27,4 %	29,0 %	30,3 %	31,4 %	32,3 %
2055	8,3 %	14,0 %	17,8 %	20,4 %	22,4 %	24,0 %	25,3 %	26,4 %	27,2 %	28,0 %
2065	7,6 %	12,7 %	16,0 %	18,2 %	19,8 %	21,1 %	22,1 %	22,9 %	23,6 %	24,2 %
Average:	10,3 %	18,0 %	24,0 %	28,9 %	33,1 %	36,7 %	39,9 %	42,7 %	45,3 %	47,7 %

APPENDIX 3

Table 8. Average SCC percent change as a result of changing end year from 2300 to 2150.

Discount rate:	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %	9 %	10 %
Year										
2015	-51,1 %	-25,3 %	-9,7 %	-5,5 %	-1,3 %	-1,0 %	-0,3 %	-0,1 %	-0,2 %	-0,5 %
2025	-51,9 %	-26,6 %	-10,8 %	-6,1 %	-1,6 %	-1,2 %	-0,4 %	-0,2 %	-0,3 %	-0,6 %
2035	-53,1 %	-28,3 %	-12,3 %	-7,0 %	-2,1 %	-1,4 %	-0,5 %	-0,2 %	-0,3 %	-0,6 %
2045	-54,6 %	-30,5 %	-14,2 %	-8,2 %	-2,9 %	-1,8 %	-0,7 %	-0,3 %	-0,3 %	-0,6 %
2055	-56,7 %	-33,3 %	-16,8 %	-9,9 %	-3,9 %	-2,5 %	-1,0 %	-0,5 %	-0,4 %	-0,7 %
2065	-59,4 %	-36,9 %	-20,1 %	-12,3 %	-5,5 %	-3,5 %	-1,6 %	-0,8 %	-0,5 %	-0,8 %

Table 9. Average SCC percent change as a result of changing end year from 2300 to 2200.

Discount rate:	1 %	2 %	3 %	4 %	5 %	6 %	7 %	8 %	9 %	10 %
Year										
2015	-28,3 %	-9,5 %	-1,7 %	-2,2 %	0,0 %	-0,6 %	-0,2 %	-0,1 %	-0,2 %	-0,5 %
2025	-28,7 %	-9,9 %	-1,9 %	-2,3 %	-0,1 %	-0,6 %	-0,2 %	-0,1 %	-0,2 %	-0,5 %
2035	-29,2 %	-10,6 %	-2,3 %	-2,4 %	-0,1 %	-0,6 %	-0,2 %	-0,1 %	-0,2 %	-0,6 %
2045	-30,0 %	-11,4 %	-2,8 %	-2,6 %	-0,2 %	-0,7 %	-0,2 %	-0,1 %	-0,2 %	-0,6 %
2055	-31,1 %	-12,4 %	-3,4 %	-2,8 %	-0,3 %	-0,7 %	-0,2 %	-0,1 %	-0,2 %	-0,6 %
2065	-32,4 %	-13,8 %	-4,3 %	-3,2 %	-0,5 %	-0,8 %	-0,2 %	-0,2 %	-0,2 %	-0,6 %