

**Essays on the economics of
new technologies to mitigate climate change**

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List of abbreviations

BECCS	Bioenergy with carbon capture and storage
BI	Basic information
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CE	Climate engineering
COP21	Conference of the Parties to the United Nations Framework Convention on Climate Change
CRT	Cognitive reflection test
CV	Contingent valuation
DB	Database
IEA	International Energy Agency
EE	Reinforced expansion of renewable energies and improvement of energy efficiency
FI	Full information
GE	Geoengineering
GHG	Greenhouse gases
GT	Gigatonnes
IPCC	Intergovernmental panel on climate change
NEP	New ecological paradigm
NGO	Non-governmental organization
NIMBY	Not in my backyard
PVQ5X	Schwartz Personal Value Questionnaire
UK	United Kingdom
RM	Radiation management
SPICE	Stratospheric particle injection for climate engineering
SRM	Solar radiation management
SRMGI	Solar radiation management governance initiative
TTIP	Transatlantic Trade and Investment Partnership
WTP	Willingness to pay
WTP ^L	Lower bound of willingness to pay
WTP ^U	Upper bound of willingness to pay

Overview of papers and co-authorship

This dissertation contains the following five papers:

- I. Merk C, Pönitzsch G, **Kniebes C**, Rehdanz K, Schmidt U, 2015. Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, 130(2), 299-312
- II. **Braun C**, Rehdanz K, Schmidt U, 2016. Validity of willingness to pay measures under preference uncertainty. *PLoS ONE*, forthcoming
- III. **Kniebes C**, Merk C, Pönitzsch G, Rehdanz K, Schmidt U, 2014. Informed and uninformed opinions on new measures to address climate change. *Kiel Working Paper*, 1936, Kiel Institute for the World Economy
- IV. **Braun C**, Rehdanz K, Schmidt U, 2016. Exploring public perception of environmental technology over time. *Kiel Working Paper*, 2027, Kiel Institute for the World Economy
- V. **Braun C**, 2016. Not in my backyard: CCS storage sites and public perception of CCS. *Kiel Working Paper*, 2028, Kiel Institute for the World Economy

Each co-author contributed significantly to the concept, design, and content of the articles.

Introduction

Anthropogenic climate change refers to the production of greenhouse gases (GHG) emitted by human activity. Since the beginning of industrialization around the mid-18th century, the amount of greenhouse gases in the atmosphere has steadily increased. Fossil fuels, such as coal and oil, are major contributors, accounting for the vast majority of human caused GHG emissions. These gases trap additional heat in the atmosphere, thereby gradually increasing the average global temperature. This rise in temperature is known as global warming.

The Intergovernmental Panel on Climate Change (IPCC) estimates that in the absence of effective climate policies, the average global temperature will increase by 1.4°C to 5.8°C between 1990 and 2100 (IPCC 2014). The long-term consequences of this increase in global temperatures will be increasingly harmful, especially if nations fail to establish effective climate policies and continue 'business as usual' in the coming decades. The IPCC expects that the increase in global temperatures will almost certainly lead to a rise in sea levels. It is also very likely that extreme weather become more frequent, threatening communities around the world. Both the frequency of heat waves and the number of heavy precipitation events will increase in many regions and more areas will be affected by longer droughts (IPCC 2012; 2013).

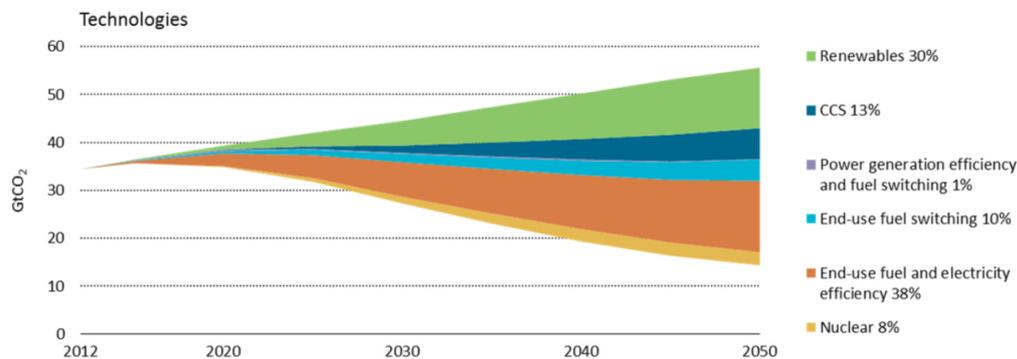
To avert these consequences and fight climate change, international action is urgently required to establish effective climate policies. In fact, in December 2015 on the United Nations Climate Change Conference in Paris (COP21), 195 countries adopted the first universal climate agreement to keep global warming below 2°C and to pursue efforts to limit it to 1.5°C. This agreement demonstrates that these nations now recognise the urgent need to reduce global greenhouse gas emissions.

However, even if economies worldwide shift towards low-carbon economies, nearly all projections suggest that the 2°C target can only be achieved by the use of technologies that either extract CO₂ from the atmosphere or capture CO₂ before it is released into the atmosphere (International Energy Agency 2015; IPCC 2014). The former technologies are known as climate engineering (CE) technologies, the latter technologies as carbon capture and storage (CCS). In fact, the large-scale use of CCS and bioenergy with CCS (BECCS) from about 2030 on is a key factor for reaching the 2°C target in the IPCC scenarios (IPCC 2014). Recent projections by the International Energy Agency (IEA) come to similar conclusions. They suggest that by 2050, CCS will account for 13 per cent of the cumulative emissions reductions that are needed to limit the global increase in temperature to 2°C (see Figure 1; International Energy Agency 2015). Without CCS, the global temperature might increase by as much as 6°C according to these projections.

The IPCC not only discussed CCS but also CE technologies as a potentially promising tool to counteract climate change (IPCC 2013). Consequently, CE technologies are often considered an important part of

an integrated response for a climate change risk management strategy (Rickels et al. 2011), although research on CE is still at an early stage and most CE technologies are less fully developed than CCS.

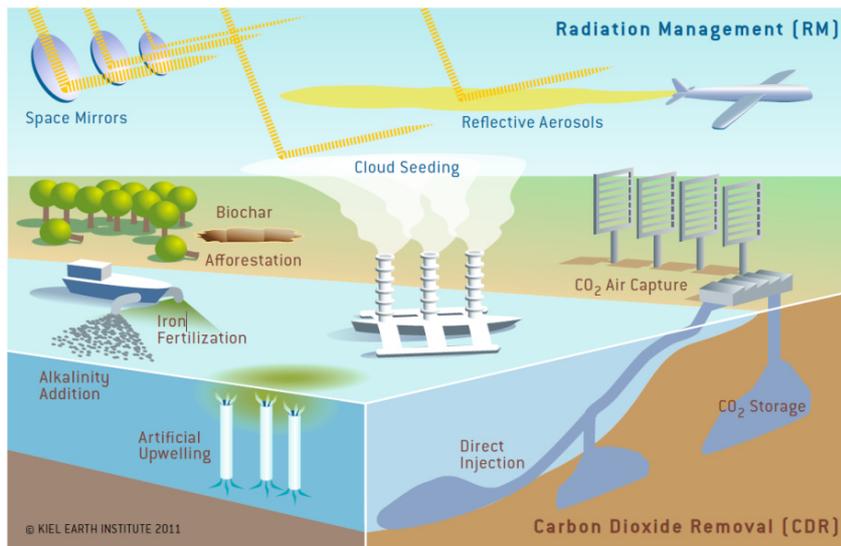
Figure 1: Contribution of technologies and sectors to global cumulative CO₂ reductions



Source: International Energy Agency (2015)

Both CE and CCS technologies involve large-scale interventions into the earth's climate system. CCS directly reduces the amount of emissions released into the atmosphere (Keith 2000). The technology separates CO₂ from other gases produced at large industrial process facilities, such as coal and cements plants, and stores it before it can enter the atmosphere. In contrast, CE technologies do not prevent fossil-fuel emissions into the atmosphere. Instead, they are applied after the CO₂ has been released into the atmosphere (Rickels et al. 2011). In general, CE encompasses two broad approaches: Solar radiation management (SRM) and carbon dioxide removal (CDR) (Royal Society 2009). Figure 2 provides a schematic illustration of SRM and CDR technologies. SRM technologies offset the impacts of radiative forcing by directly influencing the radiation budget via injecting particles or aerosol precursors in the upper atmosphere. SRM has attracted considerable attention because of its potential in case of climate emergency (Royal Society 2011). In contrast to SRM technologies, CDR technologies address the cause of radiative forcing by reducing the concentration of atmospheric CO₂ (Rickels et al. 2011). CDR technologies include large-scale afforestation, enhancing uptake of CO₂ by the oceans through iron fertilization, or increasing alkalinity.

Both research and public discourse on new climate change mitigation technologies are still in their early stages. The costs, benefits, and risks of these new technologies, and especially those of CE technologies, are currently not well understood, and large uncertainties remain regarding their effectiveness and side effects (Royal Society 2009; Keith 2014). Current debates on these new technologies are dominated by academics, representatives from the business community, non-governmental organizations (NGOs), and governments, but do usually not involve the broader public (Rickels et al. 2011).

Figure 2: Schematic illustration of CE technologies

Source: Rickels et al. (2011)

While only additional research will tell us more about the cost and benefits of CE and CCS technologies, even limited field research on CE and CCS faces widespread public protests. For instance, pilot CCS projects in the East German town of Beeskow and the North German state of Schleswig-Holstein faced strong opposition from local politicians and the wider public. As a consequence, these projects were delayed or even stopped (Dütschke 2010). Likewise, a planned outdoor test in the UK that was meant to test the feasibility of injecting particles into the stratosphere had to be postponed amidst heavy controversies about SRM. The panel overseeing the project raised concerns about the governance of the project and called for more public engagement (New Scientist 2012; Pidgeon et al. 2013).

These examples tentatively show that public acceptance will crucially determine the future of research on CE and CCS and therefore the future of CE and CCS overall. So far, however, empirical evidence on the public perception of new technologies to mitigate climate change is very limited.

Against this background, this dissertation analyses empirically the public perception of new climate change mitigation technologies in Germany and explores potential determinants. The empirical analysis uses data from eight novel surveys, which I compiled between 2012 and 2014 with colleagues at the Kiel Institute for the World Economy. The surveys are representative for internet users in Germany, and contain data on more than 5700 individuals. The focus of my analysis is on the public perception of two CE measures – namely solar radiation management via the injection of sulphate into the stratosphere and large-scale afforestation – and on CCS.

My key research objectives in this dissertation include the following:

1. To investigate factors that drive the public perception of CE and CCS technologies, and compare the perception of individuals who are well informed about a technology with those who are less informed.
2. To explore how public perception changes over time, and is influenced by transient emotions.
3. To contribute to methodological questions on how the willingness to pay for the avoidance or deployment of a CE technology can be elicited.

I pursue these three research objectives in five papers:

Paper I analyses how the German public perceives different types of research and deployment of SRM. It investigates perceptions of SRM for Germany, a country in which public perceptions of SRM have not previously been studied. Furthermore, the paper sheds light on factors that drive public acceptance of SRM such as the perceived seriousness of climate change, risk aversion, attitudes toward SRM, ecological attitudes, trust in institutions, religiosity, and socio-demographic characteristics.

Paper II elicits for the first time the willingness to pay (WTP) for the avoidance of SRM. The paper compares the performance of two methods for eliciting the WTP of SRM in the field. The first method is the traditional approach for eliciting a single value (Point-WTP). It requires that respondents know their preferences with certainty. The second method is new to the literature and elicits the WTP as a range (Range-WTP). It explicitly allows for preference uncertainty in responses. The findings in the paper support earlier criticism of the traditional open-ended Point-WTP method and show that the Range-WTP method clearly outperforms the Point-WTP method.

Paper III provides empirical evidence on the public perception of two different CE technologies, namely on SRM and afforestation, as well as CCS. It analyses the determinants of acceptance of these measures in Germany and provides experimental evidence on how additional information on these technologies changes respondents' acceptance. The results show that the acceptance differs strongly between the three technologies: Respondents generally prefer afforestation over CCS and SRM. This ranking holds independent of the amount of information provided. In any case, on average, additional information decreases acceptance. However, the sign and the strength of the information effect strongly depend on personal characteristics, such as gender and risk attitude. Overall, the paper provides a first projection on how public opinions might evolve in the future when more information on the risks and benefits of CE and CCS become available.

Paper IV sheds light on the development of public opposition against SRM over time. It shows that public opposition against SRM decreases over time. SRM first arouses strong negative emotions, but these emotions decline over time—and with them opposition against SRM. These findings suggest that initial opposition towards SRM need not to be permanent and that it might be useful to elicit the attitudes over a longer time period.

Paper V focusses on the public perception of CCS in Germany. It provides empirical evidence on how living close to a potential storage site affects the acceptance of CCS. Respondents who live close to a potential CCS storage site reveal significantly lower acceptance rates of CCS than those who do not. These results suggest that placing a CCS storage site is likely to meet fierce local resistance.

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Paper I: Exploring public perceptions of solar radiation management

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Abstract:

Solar radiation management (SRM), by the injection of sulphate aerosols into the stratosphere, could quickly offset global warming caused by anthropogenic greenhouse gas emissions. Because the technology would have global side effects, it raises not only technological but also political, ethical, and social concerns. Therefore, research on SRM should be accompanied by a global debate that incorporates public perceptions and concerns into the development and governance of the technology. Our paper provides insight into public perceptions and explores their underlying patterns using a survey conducted in Germany. The data reveal a differentiated picture. Laboratory research on SRM is broadly approved, whereas field research is much less approved. Immediate deployment is largely rejected. The acceptance of the technology is associated with the belief that climate change is a serious problem and that humans will eventually be able to control nature. It is also determined by the levels of trust in scientists and firms. Among the strongest objections against the technology is the belief that humans should not manipulate nature in the way SRM would. The actual public perceptions of SRM will, however, evolve along with the ongoing debate between the public, experts, and policymakers.

Note: A modified version of this paper is published as: Merk C, Pönitzsch G, Kniebes C, Rehdanz K, Schmidt U, 2015. Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, 130(2), 299-312. The final publication is available at <http://link.springer.com/article/10.1007%2Fs10584-014-1317-7>.

1. Introduction

New technological options to reduce global warming are currently under discussion because international efforts to mitigate climate change continue to progress slowly. These options, known as climate engineering (CE) or geoengineering (GE), involve deliberate large-scale interventions in the climate system to reduce global warming. They increasingly appear in mass media, enter political discussions (Mercer et al. 2011), and were recently mentioned in the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC 2013).

CE encompasses two approaches. The first approach, carbon dioxide removal (CDR), is to reduce atmospheric concentrations of carbon dioxide. The second approach, solar radiation management (SRM), is to increase the Earth's albedo to reflect more sunlight back into space. Our paper addresses the most prominent and controversial method of SRM, which is the injection of sulphate aerosols into the stratosphere. For simplicity we will refer to this technology as SRM. In contrast to other methods to counteract climate change, SRM can be deployed quickly and causes direct reductions in global temperature (Robock et al. 2008). In addition, it has been suggested that it involves low operational costs (Barrett 2008). Such claims, however, ignore additional economic costs like price and external effects (Rickels and Klepper 2012). Especially external effects could result in very high total costs because the risks of SRM are substantial and global (Royal Society 2009).

A comprehensive discussion is needed to support informed decisions on research and deployment of SRM because the technology involves a deliberate manipulation of the Earth's environmental system, there are major uncertainties regarding its side effects, and the consequences of its use are global. The assessment thus must address legal, political, ethical, and social issues (see Royal Society 2009 and Rickels et al. 2011 for an overview). While expert assessments are necessary to inform the debate, the issues ultimately raise value-based questions that the public might evaluate differently than experts (Pidgeon et al. 2013). Research on public perceptions can provide initial insights into public concerns and thereby inform decisions on future research and on the potential development of the technology. Its aim is not to influence public opinion in any particular direction or to replace legitimate democratic political decision-making but to better understand the public's sensitivities and its criteria for assessing the technology (Corner et al. 2012; Carr et al. 2013).

Based on a large-scale survey conducted in Germany, we contribute to the discussion on SRM by answering two important questions: (1) how does the public perceive different types of research and deployment of SRM in different circumstances? and (2) what factors drive public perceptions of SRM?

Our first research question extends recent results on public perceptions of CE options: it includes the perceptions of different types of research on SRM and it confirms previous findings on the perceptions of SRM for a country in which public perceptions of SRM have not previously been studied. Many earlier

studies have investigated CE options in general and did not distinguish between different types of research or different circumstances of deployment. These studies also varied considerably in the level of detail they provided in describing the technology. Most referred only briefly to CE technologies as a climate change policy option (Borick and Babe 2012; Bostrom et al. 2012; Leiserowitz et al. 2012; Spence et al. 2010), while others provided more information on SRM as well as CDR technologies (Kahan et al. 2012; US GAO 2011). These studies were primarily conducted in the US and the UK. To date, two surveys have investigated public perceptions of SRM and included a section with information on the technology. Mercer et al. (2011) surveyed respondents in Canada, the UK, and the US; Sugiyama and Fujiwara (2012) surveyed respondents in Japan. They assessed the perceptions of general research, immediate deployment of the technology, emergency deployment, and complete rejection of the use of the technology.

Public awareness of CE in general and of specific CE technologies remains low. The share of people who have never previously heard about climate engineering or geoengineering ranges from 65% (US GAO 2011), to 75% (Buck 2010; Spence et al. 2010; Mercer et al. 2011; Pidgeon et al. 2012¹), and 90% (Sugiyama and Fujiwara 2012). Overall, research on public perceptions finds a low level of support for these technologies (Bellamy and Hulme 2011; Borick and Rabe 2012; Bostrom et al. 2012; Macnaghten and Szerszynski 2013) and a preference for mitigation over CE as policy option against climate change (Pidgeon et al. 2012; US GAO 2011). Accordingly, survey respondents tend to agree that using SRM to counteract climate change would be the easy way out (Mercer et al. 2011; Sugiyama and Fujiwara 2012), and workshop participants tend to be concerned about the inability of SRM to address increasing greenhouse gas emissions (Pidgeon et al. 2013).

Previous research indicates that public perceptions vary depending on the specific context. First, opinions toward deployment depend on the circumstance in which the technology would be deployed. Mercer et al. (2011) and Sugiyama and Fujiwara (2012) report higher acceptance of deployment of SRM in the case of a climate emergency compared to the case in which the technology would be deployed as soon as it were technically feasible. Second, public support for research does not necessarily entail support for actual use of the technology. Pidgeon et al. (2013) note that participants in deliberative workshops often express negative views of SRM in general but express more nuanced views of the UK research project SPICE (Stratospheric Particle Injection for Climate Engineering), which was supposed to involve field tests.² Also surveys report that research on SRM is more acceptable than actual deployment (Mercer et al. 2011; Sugiyama and Fujiwara 2012).

Public perceptions are also likely to vary between the different types of research on SRM. Research

¹ Pidgeon et al. (2012) and Spence et al. (2010) analyze the same dataset.

² <http://www.spice.ac.uk/>.

activities might be classified into laboratory research that involves the use of computer models and laboratory experiments and field research that involves the release of materials into the environment (SRMGI 2011). Different types of research involve different levels of interference with nature and potentially involve different perceived direct risks (e.g., threats to the environment) and perceived indirect risks (e.g., creating a slippery slope toward deployment). To address this issue, the present study distinguishes not only between different circumstances of deployment but also between different types of research.

Our second research question examines the factors that influence public acceptance, such as the perceived seriousness of climate change, risk aversion, attitudes toward SRM, ecological attitudes, trust in institutions, religiosity, and socio-demographic variables. Previous studies have already investigated the importance of some of these factors. The perceived seriousness of climate change increases acceptance of SRM as a potential solution to the problem (Mercer et al. 2011; Pidgeon et al. 2012; Sugiyama and Fujiwara 2012); although, the risks of massive climate change have to be weighed against the risks of SRM. Thus, individuals' level of risk aversion might be a potentially contributing factor, but its influence has yet to be researched. It might increase or decrease acceptance of SRM, depending on the extent to which individuals attribute a higher risk to massive climate change or to SRM. Our survey also includes items to examine two previously suggested arguments against the technology: that humans should not manipulate nature in this way and that using SRM to combat climate change would be the too easy way out (Mercer et al. 2011). These attitudes might also be related to beliefs about human technological ingenuity (Kahan et al. 2012) and the relationship between humans and nature (Corner et al. 2013). Thus, the survey includes items about these two aspects, which we collectively refer to as ecological attitudes. We expect that individuals with the belief that humans were meant to rule the Earth or that humans would eventually learn enough to control the environment would be more willing to accept SRM, while individuals expressing concerns about the fragility of the balance of nature might either reject or accept the technology, depending on whether it was viewed as disrupting or restoring nature (Corner et al. 2013). Another potential objection to the use of the technology is the perception that humans might be 'playing God' (Carr 2014); the survey, thus, includes religiosity to account for the role of religious beliefs.

Another relevant factor for the public perceptions of research and deployment is the governance framework and the extent to which people trust that different policy and decision makers will act responsibly. Findings from focus groups on SRM indicate that confidence in the ability of research to forecast risks and benefits as well as confidence in effective and democratic governance are prerequisites for acceptance (Macnaghten and Szerszynski 2013). These results are consistent with prior findings on the positive effect of trust in institutions on the acceptance of large-scale risks (Earle 2010). Our study therefore examines the role of trust in different actors. Socio-

demographic variables might also contribute to people's perceptions; for example, Pidgeon et al. (2012) report lower levels of support for climate engineering in general among women and individuals with a lower level of education. Our analysis therefore accounts for socio-demographic variables.

By addressing these two research questions, the study broadens and deepens the understanding of public perceptions of SRM and contributes to the previous literature in a number of ways. First, our survey is the first to explicitly distinguish between perceptions of laboratory and field research. Second, our survey is the first to study perceptions of SRM in a continental European country (Germany). Compared to other Europeans, Germans express more negative attitudes toward nuclear energy and carbon capture and storage but more positive attitudes toward wind and hydroelectric energy (European Commission 2011). Our survey provides insights into Germans' attitudes toward SRM. Third, our survey investigates a wide range of factors that might influence public perceptions of SRM. Finally, our study extends the descriptive analyses employed in previous studies (Mercer et al. 2011; Sugiyama and Fujiwara 2012) by employing a multiple regression framework to analyse the effect of these factors on public acceptance in different circumstances.

2. Survey design

We conducted an online survey to assess the perceptions of SRM among the German population in December 2012. Survey respondents were recruited from an online panel and were sampled using quotas for the characteristics gender, age, and state of residence. The sample consisted of 1040 respondents; half of the respondents were female. Respondents ranged in age from 18 to 81 years, with an average age of 47 years. Half of the respondents had a higher education entrance certificate, while the other half of the respondents had completed only lower secondary education or had no degree. As a result, respondents with a high level of education are overrepresented in the sample.

All items used in the analysis are presented in table A-1 of the appendix; responses to items were all assessed using Likert scales. The questionnaire consisted of three parts.

The first part contained questions assessing respondents' attitude toward risk, the perception of the seriousness of climate change, and ecological attitudes. The attitude toward risk was assessed on the scale from Dohmen et al. (2011) ranging from 0 ('risk averse') to 10 ('fully prepared to take risks'). In the analysis, the values were reversed to capture risk aversion. We also assessed the perception of the seriousness of climate change (Q3). Respondents' ecological attitudes were measured using 5 of the 15 items of the New Ecological Paradigm Scale (NEP, Dunlap et al. 2000). They assess attitudes toward limits to growth (Q4-1), anthropocentrism (Q4-2), the fragility of the balance of nature (Q4-3), human exemptionalism (Q4-4), and the possibility of an imminent eco-crisis (Q4-5). Both the seriousness of climate change and the NEP were measured using a four-point scale that ranged from 1 ('strongly disagree') to 4 ('strongly agree').

The second part contained a video explaining anthropogenic climate change and SRM followed by questions about the respondents' perceptions. The video consisted of animated infographics and brief bullet points that were explained by an accompanying voice-over.³ First, respondents received information on the causes and likely consequences of climate change. Mitigation, adaptation, and SRM were introduced as three options to address climate change.⁴ The video stated that SRM would not prevent all consequences of climate change and that it was not a complete substitute for mitigation. The video then presented the risks and benefits of SRM in greater detail. Because the goal was to present currently available information on the topic in a clear, scientifically accurate and unbiased manner, the information presented was based on peer-reviewed papers and scientific reports (e.g., Crutzen 2006; IPCC 2007; IPCC 2012; Rickels et al. 2011; Robock 2008); it reflects the broad consensus on climate change and the risks and benefits of SRM at the time. Information on the technology was based in part on previous work (Mercer et al. 2011). Independent experts reviewed the information presented for clarity and accuracy.

Before the video, participants' level of awareness of the technology was assessed (Q5). After the video, one item assessed the acceptance of laboratory research (Q10-1) and another item assessed the acceptance of field experiments (Q10-2). Following Mercer et al. (2011) and Sugiyama and Fujiwara (2012), respondents were asked about their acceptance of deployment in different circumstances: to avert massive and irreversible changes in the climate system due to climate change, i.e., in case of a climate emergency (Q10-3); as soon as the deployment of the technology was technically feasible, which we refer to as 'immediate deployment' (Q10-5); or never, under no circumstances (Q10-4). The response scale for all these items (Q10) ranged from 1 ('strongly disagree') to 4 ('strongly agree'). All these scenarios imply a continuation of mitigation efforts. The perception of overall benefit (Q11) and overall risk (Q12) was measured on a scale ranging from 1 ('very small') to 4 ('very large'). The specific risks (Q13) and benefits (Q14) appeared in the questionnaire with the same wording which was used in the video; respondents' perceptions were measured on a scale ranging from 1 ('negligible') to 4 ('very serious') (Q13) and from 1 ('very small') to 4 ('very large') (Q14), respectively. We also measured the extent to which respondents agreed with four items expressing different attitudes toward SRM. For example, the statement 'Humans should not be manipulating nature in this way' (Q17-3) was assessed on a scale ranging from 1 ('strongly disagree') to 4 ('strongly agree'). Trust that different institutions or actors would act in the interest of society and the environment was measured on a scale ranging from 1 ('do not trust at all') to 4 ('trust completely').

³ An English translation of the German video script is provided in the appendix.

⁴ The video initially described SRM as 'spraying sulfate particles into the atmosphere at high altitude' to reflect sunlight. When subsequently referring to the technology, both the video and the survey used the term 'solar radiation management' or the abbreviation 'SRM'.

The third part contained questions on respondents' socio-demographic characteristics that were not available from the panel's database. We have information on respondents' gender, age, and state of residence as well as other characteristics, such as the level of education⁵ or whether the respondent had children. In addition, we assessed respondents' religiosity (Q26) on a scale ranging from 1 ('not religious at all') to 4 ('very religious'). At the end of the questionnaire, respondents had the opportunity to make comments on SRM (Q36). 78% of the respondents made 1436 different statements in total. The statements were coded by a research assistant who was otherwise not involved in the research.

3. Descriptive results

In the following, we describe responses to the questionnaire. When appropriate, we aggregate responses from the four-point Likert scales into two categories. For example, we speak of agreement when respondents choose the categories 'strongly agree' or 'somewhat agree'. Correspondingly, we speak of disagreement when respondents choose the categories 'strongly disagree' or 'somewhat disagree'.

Public awareness and perceptions of the video

Currently, the German population does not exhibit widespread awareness of SRM. Before watching the video, 80% of the respondents state that they have not previously heard about spraying sulphate particles into the atmosphere at a high altitude to counteract climate change; 17% recognize the technology and state that they had heard a little about it; and 3% state that they had heard a lot about it (Q5). After watching the video, 80% state that they perceived the video's position toward SRM as neutral; 13% state that the video was biased in favour of the technology; and 1% stated that the video was biased against it (Q9). Only ten of the 1040 respondents report difficulties in understanding the video (Q8).⁶

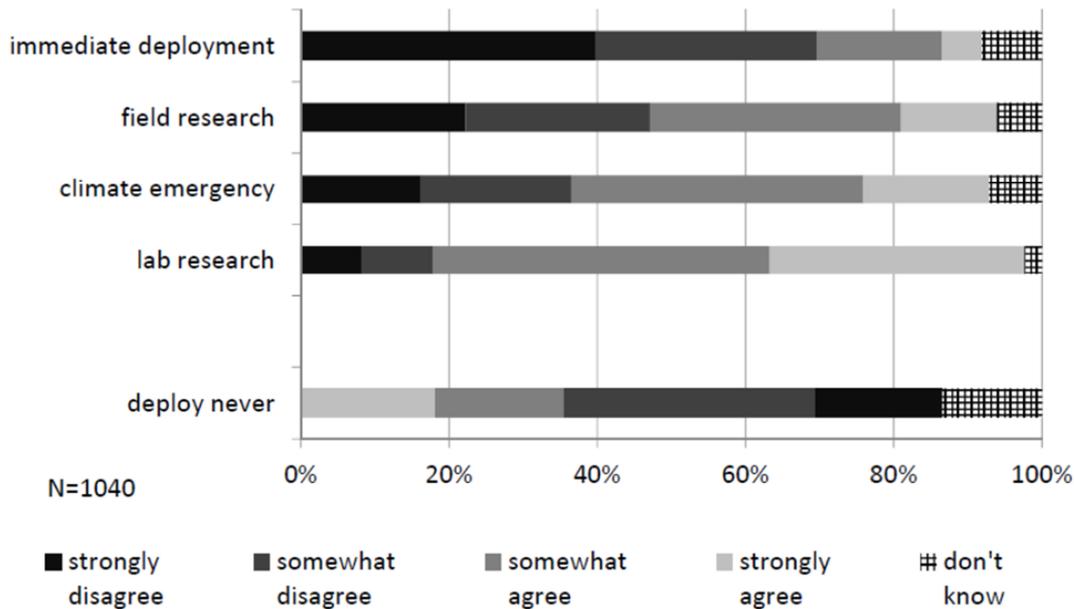
Acceptance

Figure 1 summarizes the findings regarding acceptance of the different types of research and acceptance of deployment in different circumstances. Laboratory research is widely accepted; with 80% of respondents agreeing that scientists should study SRM through computer models and laboratory experiments (Q10-1). Acceptance of field research involving small-scale experiments in the atmosphere is markedly different; only 47% of the respondents are in favour of field research (Q10-2). This implies that approximately one-third of the respondents believe that research should be conducted in the laboratory but not in the field.

⁵ Respondents with a higher education entrance certificate were coded as having a high level of education in the analysis.

⁶ Respondents were not able to skip or fast forward the video.

Figure 1: Acceptance of different types of research and of deployment in different circumstances.



Note: Agreement with this item reflects the rejection of SRM.

The most accepted circumstance for deployment is in case of a climate emergency. Slightly more than half of the respondents (56%) agree with deployment in this case (Q10-3). The relatively high acceptance of emergency deployment indicates that some respondents support emergency deployment despite their opposition to field research. The most immediate form of deployment is as soon as it is technically feasible (Q10-5). 22% of the respondents support immediate deployment, while 70% of the respondents disagree – many of them indicating strong disagreement. 35% of the respondents agree that SRM should never be used regardless of the situation (Q10-4), with 18% of all respondents strongly agreeing that the technology should never be used. In summary, the respondents’ opinions regarding SRM vary across types of research and circumstances of deployment.

Attitudes toward SRM

We explore key attitudes toward SRM using further questions. More than 70% of the respondents think both that humans should not be manipulating nature in this way (Q17-3) and that using the technology to counteract climate change would mean to take the too easy way out (Q17-1).⁷ Both attitudes also feature prominently in the free-form comments made at the end of the survey. Many respondents voice concerns that humans should respect nature and ‘not play God’. Others state that the causes rather than the symptoms of climate change should be addressed.

⁷ The connotation of the German expression for taking the too easy way out is that SRM cannot be right; taking the too easy way out is considered to shirk one’s responsibility or to be thoughtless.

A strong concern in the discussion about the technology is about the final decision regarding implementation. Specifically, research on SRM might create a slippery slope toward its implementation. Respondents express the belief that research into the technology would lead to its deployment no matter what the public thinks (Q17-2); 71% of the respondents agree with this statement. The strong concern about the deployment decision is also visible in the free-form comments. The comments express the need to involve all nations as well as the general public in the decision-making process.

Perceptions of risks and benefits

We asked respondents to judge the extent of the overall risk of SRM and the severity of its specific risks. The overall risk (Q12) is perceived as large; 81% of the respondents view the risk as very large or somewhat large, and 42% view the risk as very large.

Respondents exhibit the most concern about the abrupt temperature change that would be caused by a sudden termination of SRM (Q13-4) and the risk of yet unknown and unpredictable consequences (Q13-3). For both these risks, at least 88% of the respondents perceive them as serious. 85% of the respondents perceive changes in precipitation as a serious risk (Q13-1). Respondents exhibit only slightly less concern about the persistence of carbon-intensive lifestyles if SRM were deployed (Q13-2). Finally, international conflicts caused by trans-boundary side effects (Q13-5) are perceived as a serious risk by 72% of the respondents.

The perception that the risks are serious is dominant; any specific risk is viewed as serious by more than 72% of the respondents. Moreover, apart from the risk of international conflict, 45% of the respondents view each specific risk as very serious. Concerns about specific risks are also frequently mentioned in the free-form comments.

Similarly, we asked respondents to judge the extent of the overall benefit and specific benefits of SRM. In contrast to the perceptions of risks, the perceptions of benefits show a higher variance across respondents. The overall benefit (Q11) is perceived to be small by 51% of the respondents, and perceived to be large by 41% of the respondents. Only few responses fall into the categories 'very large' (6%) or 'very small' (12%); respondents do not display extremely positive or negative opinions regarding the overall benefit of SRM.

The evaluation of specific benefits yields a differentiated picture. The possibility of preventing massive, irreversible changes in the climate (Q14-2) is most often perceived as a large benefit of the technology; 54% of respondents perceive this benefit as large. The speed at which the climate can be cooled (Q14-1) comes second; 51% perceive this benefit as large. The possibility of unilaterally deploying SRM (Q14-4) and the comparatively low costs of implementation (Q14-3) are less often rated as beneficial; 42% and 35% of the respondents perceive these benefits as large, respectively.

4. Regression analysis

To further analyse public acceptance of SRM and its underlying patterns, we conducted a regression analysis.

As predictors of acceptance, we used the variables that were discussed in section 1 and described in section 2. The econometric model thus includes independent variables capturing risk aversion, perceived seriousness of climate change, ecological attitudes, trust in different institutions, attitudes toward SRM, religiosity, and socio-demographic factors.⁸ We did not include the awareness of SRM because the variable shows too little variation. The dependent variables capture acceptance in different circumstances and take ordered values ranging from 1 ('strongly disagree') to 4 ('strongly agree'). We hence used ordered logistic regression as the estimation procedure.

Table 1 presents the regression results. The columns display regression results for (1) laboratory research, (2) field research, (3) deployment in case of a climate emergency, and (4) immediate deployment.

Most of the explanatory variables have a significant effect on acceptance. Risk aversion (Q2) negatively affects the acceptance of field research and immediate deployment. The perceived seriousness of climate change (Q3) increases the acceptance of field research and of deployment in case of a climate emergency. In contrast, the perceived seriousness of climate change does not increase the acceptance of immediate deployment. This finding is in line with the consequences of climate change primarily occurring in the future and the belief that serious consequences might still be averted by other means.

With respect to ecological attitudes, the belief in human exemptionalism (Q4-5), i.e., humans' ability to control the environment, displays the strongest predictive power. It has a strong positive effect on people's acceptance of field research and deployment. The risk of an eco-crisis (Q4-6) predicts acceptance of immediate deployment. Because the item reflects beliefs about the imminence of a crisis, it captures the perceived need for timely action. The belief that the balance of nature is fragile and easily upset (Q4-4) increases acceptance of laboratory research, but it does not affect acceptance of implementation. Anthropocentrism (Q4-3), i.e., the belief in humans' designation to rule over nature, and the belief in limits to growth (Q4-2) only have a minor impact on acceptance. Religiosity (Q26) does not have additional explanatory power on top of the other attitudinal items in the model.

Apart from general attitudes toward the environment and the human-environment interaction, the belief that humans should not manipulate nature in this way (Q17-3) strongly decreases acceptance of research and deployment. It also decreases acceptance of the technology as a way to counteract a climate emergency. The attitude that SRM would be the too easy way out (Q17-1) decreases the

⁸ Summary statistics are available in table A-2 in the appendix.

acceptance of immediate deployment. This result is consistent with the notion that deployment should only be considered when every other option has been exhausted.

Table 1: Results obtained from ordered logistic regressions

	(1) lab research	(2) field research	(3) emergency deployment	(4) immediate deployment
(Q2) risk aversion	-0.04	-0.07**	-0.01	-0.06*
(Q3) seriousness of climate change	0.16	0.28**	0.41***	0.11
<i>Ecological attitudes</i>				
(Q4-2) limits to growth	0.20*	0.03	0.08	-0.02
(Q4-3) anthropocentrism	0.18*	0.11	0.04	0.18
(Q4-4) balance of nature	0.36***	-0.03	-0.03	-0.16
(Q4-5) hum exemptionalism	0.09	0.33***	0.53***	0.28**
(Q4-6) risk of an eco-crisis	0.06	0.24*	0.17	0.67***
<i>Attitudes</i>				
(Q17-1) is too easy way out	0.04	-0.13	-0.01	-0.52***
(Q17-3) not manipulate this way	-0.66***	-0.83***	-0.93***	-0.73***
<i>Trust</i>				
(Q23-1) government	-0.17	0.34***	0.16	0.13
(Q23-2) firms involved	0.01	0.37***	0.19	0.79***
(Q23-3) environmental org	0.22**	-0.02	0.08	-0.19
(Q23-4) media	0.09	0.08	0.09	-0.03
(Q23-5) scientists	0.91***	0.68***	0.88***	0.40***
(Q23-6) United Nations	-0.08	-0.09	0.05	0.00
(Q23-7) European Union	0.21	0.02	-0.01	0.37**
<i>Socio-demographics</i>				
(Q26) religiosity	-0.10	-0.09	0.05	-0.01
(DB) female	-0.20	0.14	0.09	-0.14
(Q34) high education	0.02	-0.27*	-0.31*	-0.70***
(DB) age	-0.01	0.00	-0.01*	0.01**
(Q32) children	-0.15	0.26	0.13	0.31
N	682	682	682	682
Pseudo R ²	0.17	0.23	0.25	0.30

***, **, * indicate significance at the 1%, 5%, and 10% level, respectively. Scales are from 1 to 4. Exceptions are dummy variables (female, high education, and children), risk attitude (scale is from 0 to 10), and age. Variables indicated by (DB) are part of the panel's database.

Trust that different institutions or actors would act in the interest of society and the environment significantly affects acceptance. The most important determinant from this group of variables is trust in scientists (Q23-5) who perform research on SRM. Another important determinant is trust in firms (Q23-2) involved in SRM projects. Trust in firms is a prerequisite for the acceptance of field research and immediate deployment. For the acceptance of laboratory research, however, in which firms' involvement is likely to be low, trust in firms is not a significant predictor. Trust in firms is also not a significant predictor for the acceptance of deployment in case of a climate emergency. In this circumstance, typical problems with respect to firms, such as vested interests, might be expected to play a minor role. Trust in government (Q23-1) is another predictor of acceptance, although it is not as important as trust in scientists or firms. First, trust in the federal government is positively associated

with the acceptance of field research. This relationship might reflect trust in the rules for research set by the government. Second, trust in the EU is positively associated with the acceptance of immediate deployment. Trust in environmental organizations (Q23-3) is only modestly associated with acceptance after controlling for ecological attitudes. Trust in environmental organizations is positively associated with the acceptance of laboratory research, which may reflect a lower perceived risk of hasty deployment. Trust in the media (Q23-4) does not predict acceptance.

In addition, the socio-demographic variables education and age exhibit explanatory power. A high level of education (Q34) reduces the acceptance of field research and deployment. This finding might reflect differences in information processing, in dealing with complexity, or in socio-economic status. The level of education most strongly affects the acceptance of immediate deployment. The effect of age depends on the circumstance of deployment. Age is positively related to the acceptance of immediate deployment but negatively related to the acceptance of emergency deployment. These relationships are not consistent with an inter-temporal risk-risk trade-off and thus point to particular intergenerational differences in the perceptions of SRM. Neither gender nor having children (Q32) are related to acceptance of the technology.

Our results proved to be robust to alternative specifications. First, we checked whether it is appropriate to include the independent variables as continuous variables by running regressions using binary indicators for the levels of these variables. The results confirm that the effects of the independent variables are linear.⁹ Second, we checked for differences in acceptance across German states to control for interregional differences in factors, such as religious composition or population density. The results are not significantly different. Finally, we ran regressions using binary and multinomial logistic models. The direction and the significance of the coefficients remain similar.

5. Discussion and conclusion

Overall, German respondents are highly sceptical of SRM. The views depend on the type of research and the circumstance of deployment. First, respondents' higher acceptance of laboratory research compared to field research reveals their concern regarding the negative side effects of field research. The finding highlights the importance of (1) identifying what can be learned without actually intervening in the Earth's environmental system (Robock et al. 2013), (2) identifying the type of research to be performed when communicating with the public and (3) establishing a governance framework for research (SRMGI 2011). Second, the higher level of acceptance of emergency deployment compared to immediate deployment reflects respondents' belief that climate change might still be averted by other means. Finally, the higher level of acceptance of laboratory research compared to any type of deployment suggests that respondents perceive laboratory research as a means to better understand

⁹ Results of this robustness check are presented in table A-3 in the appendix.

the technology's side effects or as a way to develop an insurance against massive and irreversible climate change.

The distinction between different circumstances and their implications is also relevant when examining the factors influencing acceptance of the technology. The perceived seriousness of climate change is positively associated with acceptance of research and emergency deployment. Faced with the risk-risk trade-off between climate change and SRM, respondents who are more concerned about climate change seem not to want to dismiss the technology out of hand. Additionally, the perception that SRM would be taking the too easy way out, i.e., shirking the responsibility for climate change, decreases the acceptance of immediate deployment but does not reduce the acceptance of research. This suggests that spending money on researching SRM rather than mitigation is not currently viewed as problematic.

We also examine beliefs about the relationship between humans and nature as potential determinants of acceptance. The perceived fragility of the balance of nature, however, is neither positively nor negatively associated with the acceptance of the deployment of SRM, which reflects the unresolved debate on whether the technology is beneficial or detrimental to nature (Corner et al. 2013; Rickels et al. 2011). However, the positive association of this belief with the acceptance of laboratory research again reveals the perceived value of SRM as a way to insure against climate change. In contrast, the belief about human interaction with nature strongly influences acceptance. Respondents who believe that humans will eventually be able to control the environment are more accepting of the technology, which might reflect a trust in technology and humans' ability to devise a technological solution to the problem.

The belief that humans should not manipulate nature in this way exhibits the strongest downward impact on acceptance for all types of research and circumstances of deployment. This belief might be interpreted in various ways. It is not associated with religious concerns (Spearman's $\rho = -.02$; $p = .6$) but it is positively correlated with risk aversion (Q2; $\rho = .11$; $p < .01$) and negatively correlated with the beliefs that humans should govern nature (Q4-3; $\rho = -.22$; $p < .001$) and that humans were able to control nature (Q4-4; $\rho = -.23$; $p < .001$). It is also strongly correlated with the belief that climate change should be dealt with differently (Q17-1; $\rho = 0.50$, $p < .001$). Because these factors were controlled for in the regression analysis, the belief that humans should not manipulate nature in this way is likely to represent further aspects that influence acceptance, such as the novelty or the perceived naturalness of the technology. Once people become familiar with the concept of SRM, they might perceive the technology differently. In particular, this change in familiarity might be accompanied by a change in the public's conceptualization of nature and the human-environment interaction (Hansen 2006). The dynamics of people's attitudes toward SRM provide an interesting avenue for future research.

Among the socio-demographic variables, both the level of education and age are significantly associated with acceptance. The specific mechanisms underlying these relationships merit further research as well.

As expected, trust in relevant actors is an important determinant of acceptance. Trust in scientists is the most important prerequisite. This is consistent with the high level of uncertainty regarding the risks of SRM. Trust in firms is important with respect to field research and immediate deployment because the vested interests of firms and a lack of public involvement might create a slippery slope in which research leads to deployment of the technology. These findings indicate that transparency in research and technology use must be a key component of any governance framework and thus highlight one of the Oxford Principles (Rayner et al. 2009).

Overall, our results indicate that SRM is primarily acceptable when it is viewed as an insurance against massive climate change, i.e., a risk management tool. This is consistent with previous research findings that mitigation is preferred to SRM (Pidgeon et al. 2012; US GAO 2011). At the same time, our results reveal that the technology cannot be easily dismissed on the grounds of public acceptance. They highlight the need for appropriate decision-making structures to ensure democratic legitimacy (Victor 2008; Virgoe 2009), to improve decision making, to establish trust, and to respect ethical standards (Carr et al. 2013).

We examine public concerns in Germany, a country in which public perceptions of SRM have not previously been studied. Compared to the results of similar surveys in other countries (Mercer et al. 2011; Fujiwara and Sugiyama 2012), our findings exhibit either a similar pattern of responses or somewhat more critical responses. Our respondents are more likely to perceive SRM the too easy way out and less likely to accept immediate deployment of the technology. However, the comparability of the studies is limited due to differences in the information presented, the wording of the questions, and the questionnaire design. To ensure a broad and comprehensive dialogue regarding SRM, it is critical to identify public perceptions and concerns for a wide range of countries and cultures. Future surveys should allow for direct comparison of results from a representative set of countries that includes developing countries and the countries that are most vulnerable to the effects of climate change. In addition, our survey investigates several factors influencing public perceptions. These factors might be expected to vary for different countries, such as the level of trust in institutions (WVS 2013) and concern for the environment (Marquart-Pyatt 2012). Conflict lines are thus likely to occur at both the national and international level.

As other survey results, our findings must be interpreted cautiously. Corner et al. (2012: 454) note that respondents' lack of prior knowledge of the topic creates the risk that "...participants have been told what they are responding to rather than deciding for themselves how to interpret the item." We therefore paid specific attention to ask balanced questions without leading cues. In addition, the `don't

know' option was included in every item to signal that not answering was acceptable. The sequence of items within the questions was randomized, and we arranged the questions in a way that prevents or minimizes bias due to order effects. We also consulted with experts on survey design to ensure that our questionnaire met current quality standards. We paid specific attention to frame the video in a balanced and neutral way. It must be noted, however, that the way in which information is framed might influence responses (Corner and Pidgeon 2014). Our results thus provide a snapshot of public perceptions obtained in a highly controlled setting in which the video was the main reference point for respondents' perceptions. Although our sample is broadly representative of the German population, our respondents' views may not reflect actual public perceptions once the technology is more widely known and different framings enter the public discourse.

Despite these limitations, our survey makes a valuable contribution to the emerging public debate on SRM. With regard to future research, our results provide a useful reference point because our respondents' perceptions were not influenced by previous public discourse or extensive media coverage but by a well-documented video. Our results provide information about public concerns that should prove useful for experts and policymakers and that could be incorporated into the formal assessment of the technology and development of a governance framework. To avoid a slippery slope toward premature deployment, it is imperative that public concerns about SRM be explored at an early stage (Carr et al. 2013; Corner et al. 2012) because the public can identify and discuss critical aspects of a technology even when relatively little information on the topic is available (Corner et al. 2012; Macnaghten and Szerszynski 2013). Our results thus provide a first glimpse of public concerns and opinions regarding stratospheric SRM that is relevant for public opinion researchers, experts and policymakers.

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7. Appendix

Table A-1: Items from the questionnaire

<i>Question and items</i>	<i>response scale</i>
<p>Q2: Risk attitude Are you generally a person who is fully prepared to take risks or do you try to avoid taking risks?</p>	risk averse (0) - fully prepared to take risks (10), reversed
<p>Q3: Seriousness of climate change Global warming is a serious problem.</p>	strongly disagree (1) - strongly agree (4)
<p>Q4: New Ecological Paradigm</p> <ol style="list-style-type: none"> 1 The Earth is like a spaceship with very limited room and resources. 2 Humans were meant to rule over the rest of nature. 3 The balance of nature is very delicate and easily upset. 4 Humans will eventually learn enough about how nature works to be able to control it. 5 If things continue on their present course, we will soon experience a major ecological catastrophe. 	strongly disagree (1) - strongly agree (4)
<p>Q5: Knowledge about SRM Have you ever heard about Solar Radiation Management before or have you never heard about it before?</p> <ul style="list-style-type: none"> • No, I have never heard about it. • Yes, I have heard a little about it. • Yes, I have heard a lot about it. 	
<p>Q10: Acceptance of SRM</p> <ol style="list-style-type: none"> 1 Scientists should research SRM using theoretical models, simulations and lab experiments. 2 Scientists should test SRM using field trials. 3 SRM should be used when massive and irreversible changes in the climate system are approaching which cannot be averted otherwise. 4 SRM should never be used, no matter the situation. 5 If SRM was possible today, we should use it immediately. 	strongly disagree (1) - strongly agree (4)
<p>Q11: Benefit in general Overall, what do you think about the benefits of SRM?</p>	very small (1) - very large (4)
<p>Q12: Risk in general Overall, what do you think about the risks of SRM?</p>	very small (1) - very large (4)
<p>Q13: Specific risks</p> <ol style="list-style-type: none"> 1 It changes the amount of precipitation. 2 It can take away people's motivation to change their lifestyle. 3 There is the possibility of further unknown and unforeseeable risks. 4 The abrupt increase of Earth's temperature in case of a sudden stop of SRM can lead to severe problems for humans and the environment. 5 The use of SRM could cause international conflicts. 	negligible (1) - very serious (4)

Table A-1 continued

<i>Question and items</i>	<i>response scale</i>
Q14: Specific benefits	
1 Global warming is slowed down quicker than by cutting greenhouse gas emissions.	very small (1) -
2 Massive and irreversible changes in the climate can be stopped before too much damage is done.	very large (4)
3 It is cheaper than reducing the consumption of fossil fuels.	
4 Even if certain countries do not want to reduce their greenhouse gas emissions, it is possible to stop climate change.	
Q17: Attitude toward SRM	strongly disagree (1) -
1 SRM is the too easy way out.	strongly agree (4)
2 Research into SRM will lead to a technology that will be used no matter what the public thinks.	
3 Humans should not be manipulating nature in this way.	
4 If scientists find that SRM can stop global warming with minimal side effects, then I would support its use.	
Q23: Trust in institutions	do not trust at all (1) -
How strongly do you trust that these groups will act in the interest of society and the environment?	trust completely (4)
1 Federal government	
2 Companies involved in SRM projects	
3 Environmental organizations	
4 Media	
5 Researchers studying SRM at publicly funded research institutes	
6 United Nations	
7 European Union	

Table A-2: Summary statistics

<i>variables</i>	<i>mean</i>	<i>median</i>	<i>standard deviation</i>	<i>min</i>	<i>max</i>
acceptance					
lab research	3.1	3	0.91	1	4
field research	2.4	2	1	1	4
emergency deployment	2.6	3	1	1	4
immediate deployment	1.9	2	0.95	1	4
risk aversion	5.5	5	2.3	0	10
seriousness of climate change	3.5	4	0.76	1	4
New Ecological Paradigm					
limits of growth	3.5	4	0.72	1	4
anthropocentrism	1.8	2	0.86	1	4
balance of nature	3.5	4	0.68	1	4
human exemptionalism	2.2	2	0.86	1	4
risk of an eco-crisis	3.2	3	0.77	1	4
attitude toward SRM					
SRM is too easy way out	3.2	3	0.89	1	4
Should not manipulate nature in this way	3.2	3	0.91	1	4
trust in...					
federal government	2.1	2	0.84	1	4
firms involved	1.8	2	0.82	1	4
environmental org	3	3	0.82	1	4
media	2	2	0.78	1	4
scientists	2.4	3	0.87	1	4
United Nations	2.3	2	0.84	1	4
European Union	2.2	2	0.84	1	4
religiosity	2	2	0.93	1	4
age	48	50	15	18	81
female (no/yes)	43%				
higher education entrance cert. (no/yes)	50%				
having kids (no/yes)	58%				
N=682					

Table A-3: Regressions results with categorical variables

	(1) lab research	(2) field research	(3) emergency deployment	(4) immediate deployment
risk aversion	-0.06*	-0.09**	-0.02	-0.08*
1.climate change serious	-0.31	-0.39	-0.78	-0.11
2.climate change serious	0.15	-0.91**	-1.01***	-0.77*
3.climate change serious	-0.24	-0.13	-0.27	0.28
1.NEP: limits to growth	-0.11	-0.09	-0.83	-0.39
2.NEP: limits to growth	-0.42	-0.40	0.03	0.22
3.NEP: limits to growth	-0.57***	-0.01	-0.10	0.01
2.NEP: anthropocentrism	-0.16	0.07	-0.21	0.23
3.NEP: anthropocentrism	0.30	0.38	0.08	0.26
4.NEP: anthropocentrism	1.26**	-0.24	0.16	0.37
1.NEP: balance of nature	-1.48*	0.14	1.60*	1.30
2.NEP: balance of nature	-0.52	0.42	0.24	0.12
3.NEP: balance of nature	-0.39**	-0.18	-0.27	0.11
1.NEP: human exempt.	0.06	-0.59***	-0.60***	-0.38
3.NEP: human exempt.	0.30	0.27	0.22	0.07
4.NEP: human exempt.	0.28	0.71**	1.76***	1.04***
1.NEP: eco-crisis	-1.11*	-1.59**	-1.74**	-1.13
2.NEP: eco-crisis	0.11	0.16	-0.05	-0.66**
4.NEP: eco-crisis	-0.08	0.44**	0.03	0.80***
1.too easy way out	-0.39	0.33	-0.36	1.16***
2.too easy way out	-0.04	0.39	0.20	1.50***
3.too easy way out	0.27	0.23	0.42**	0.76***
1.don't manipulate nature	2.67***	2.68***	3.46***	1.74***
2.don't manipulate nature	1.18***	1.53***	1.77***	1.66***
3.don't manipulate nature	0.74***	1.45***	1.11***	1.17***
1.trust: government	-0.24	-0.43*	-0.44*	0.10
3.trust: government	-0.66***	0.22	-0.03	0.15
4.trust: government	-0.95*	0.65	-0.06	0.32
2.trust: firms	-0.22	0.37*	0.32	0.78***
3.trust: firms	0.21	0.74**	0.58**	1.55***
4.trust: firms	-0.51	1.19**	0.29	2.39***
1.trust: environmental org	-0.97***	-0.54	-0.55	0.12
2.trust: environmental org	-0.09	0.12	-0.33	0.04
4.trust: environmental org	0.03	-0.12	-0.06	-0.23
1.trust: media	0.15	0.13	0.40*	0.09
3.trust: media	0.25	0.12	0.49**	-0.17
4.trust: media	0.31	0.97*	0.46	0.95
1.trust: scientists	-2.14***	-1.89***	-2.28***	-1.13***
2.trust: scientists	-0.66***	-0.95***	-0.74***	-0.37*
4.trust: scientists	1.01**	-0.25	0.33	0.15

Table A-3 continued

	(1) lab research	(2) field research	(3) emergency deployment	(4) immediate deployment
1.trust: UN	-0.07	0.07	0.20	-0.27
3.trust: UN	-0.12	-0.02	0.06	-0.23
4.trust: UN	-0.56	-0.61	-0.02	-0.41
1.trust: EU	-0.11	0.10	0.07	-0.47
3.trust: EU	0.16	-0.04	-0.07	0.32
4.trust: EU	1.34**	0.40	0.46	0.62
religiosity	-0.10	-0.09	0.09	0.05
female	-0.22	0.16	0.08	-0.11
high education	0.03	-0.34**	-0.27	-0.76***
age	-0.01	0.01	-0.01	0.01**
children	-0.23	0.18	0.09	0.33
N	682	682	682	682
Pseudo R ²	0.21	0.26	0.28	0.32

p values * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The base category is the category with the highest frequency count.

Information provided in the video

Sunlight warms the Earth and the Earth's atmosphere. Greenhouse gases in the atmosphere, such as CO₂, ensure that a certain amount of heat remains close to the Earth's surface. This makes the Earth warm enough for humans, animals, and plants to survive.

Since the beginning of industrialization around the year 1850, humans have emitted large amounts of greenhouse gases, for example, by burning coal, oil, and gas. These gases trap additional heat in the atmosphere and cause a gradual increase in the average global temperature.

Since 1900, the global temperature has risen on average by approximately 0.8°C. Almost all countries agree that the increase in the average global temperature should not exceed 2°C compared to the temperature at the beginning of the industrialization. This is referred to as the 2°C target.

A future temperature increase between 0.9°C and 5.4°C is expected by 2100. The outcome depends especially on the amount of greenhouse gases emitted in the future. To reach the 2°C target, the current level of emissions would have to decrease by more than half by 2050. By 2100, almost no greenhouse gases should be emitted.

Climate change will almost certainly cause a rise in sea levels. It is very likely that both the frequency of heat waves and the number of heavy precipitation events will increase in many regions. In the future, it is likely that more areas will be affected by longer droughts and that the frequency and the intensity of tropical cyclones will increase. In addition, because oceans absorb some of the CO₂ in the atmosphere, they will become more acidic.

There are different ways to deal with climate change:

We can reduce greenhouse gas emissions or adapt to the new climate – for example, by building dikes or using more robust plants in agriculture. Another option is to reduce the global temperature by deploying solar radiation management (SRM).

Through SRM, a portion of the sunlight is reflected before it can warm the Earth. This can be achieved by, for example, spraying sulphate particles into the atmosphere at a high altitude.

A similar phenomenon is observed in nature. When large volcanoes erupt, similar particles are distributed across wide areas of the Earth's atmosphere, which cools the Earth.

The particles remain in the higher regions of the atmosphere for about two years. To prevent the Earth from heating up again, spraying would have to be continued until the cause of global warming is removed. Because the emitted CO₂ stays in the atmosphere for a very long time, SRM might have to be used for several centuries. Ocean acidification will not be halted by using SRM. However, the 2°C target

could be met regardless of future greenhouse gas emissions by deploying SRM. Currently, researchers are investigating the risks, benefits, and feasibility of SRM.

The use of SRM entails benefits as well as risks. One benefit is that global warming might be slowed more quickly compared to cutting greenhouse gas emissions. This would provide mankind with additional time to remove the cause of climate change, i.e., the high concentration of greenhouse gases in the atmosphere. Massive and irreversible changes in the climate could be stopped before too much damage is done. Furthermore, it would be possible to stop climate change even if certain countries refused to reduce their greenhouse gas emissions. Deploying SRM would be cheaper than reducing the consumption of fossil fuels.

The risks include a change in the amount of precipitation in most regions. In particular, arid regions would have to cope with even less rain. If the deployment of SRM were suddenly halted, the global temperature would rise abruptly. The speed of this temperature rise might lead to severe problems for humans and the environment. Because possible side effects would occur across international boundaries, the use of SRM might cause international conflicts. Once used, SRM might take away people's motivation to change their lifestyle and the emission of greenhouse gases would continue to increase. Furthermore, there would be the threat of other unknown and unforeseeable risks.

Paper II: Validity of willingness to pay measures under preference uncertainty

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Abstract

Recent studies in the marketing literature (Wang et al. 2007; Dost and Wilkens 2012) developed a new method for eliciting willingness to pay (WTP) with an open-ended elicitation format: the Range-WTP method. In contrast to the traditional approach of eliciting WTP as a single value (Point-WTP), Range-WTP explicitly allows for preference uncertainty in responses. The aim of this paper is to apply Range-WTP to the domain of contingent valuation and to test for its theoretical validity and robustness in comparison to the Point-WTP. Using data from two novel large-scale surveys on the perception of solar radiation management (SRM), a little-known technique for counteracting climate change, we compare the performance of both methods in the field. In addition to the theoretical validity (i.e. the degree to which WTP values are consistent with theoretical expectations), we analyse the test-retest reliability and stability of our results over time. Our evidence suggests that the Range-WTP method clearly outperforms the Point-WTP method.

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1. Introduction

There is a long-lasting and ongoing debate about the best method to elicit willingness-to-pay (WTP) for contingent valuation (CV) of non-market goods in environmental (Carson 2011), agricultural (Boyle and Bishop 1988; Corrigan et al. 2009) and health economics (Diener et al. 1998; Damschroder et al. 2007). A fundamental issue in this debate is the question whether open- or closed-ended methods lead to more reliable results (Sellar et al. 1985; Kealy and Turner 1993; Frew et al. 2003). Traditional CV studies rely on an open-ended approach in which respondents are free to state any amount they wish to indicate their WTP (Arrow et al. 1993; Bateman et al. 1995). The open-ended method has been criticized for the high cognitive load it imposes on respondents, a high number of observed non- or zero responses, and the fact that the distribution of responses is typically heavily skewed towards high amounts which might be caused by a strategic bias (Donaldson et al. 1997). As an alternative, closed-ended methods have been developed where respondents select a value from a pre-specified list (payment card) or where WTP is derived from (a series of) dichotomous choices. Despite the increasing popularity of closed-ended methods, several methodological issues have been observed. While approaches relying on payment cards are subject to starting point and range biases (see e.g., Mitchell and Carson 1989; Ready et al. 1996; Venkatachalam 2004), dichotomous choices are statistically inefficient and may be prone to the 'yea-saying bias', i.e. a tendency to accept presented amounts (Kanninen 1995; Klose 1999; Smith 2000; Venkatachalam 2004; Whynes et al. 2004; Yeung et al. 2006). In view of these issues a number of authors have questioned the superiority of closed-ended over open-ended methods (Kealy and Turner 1993; Brown et al. 1996; Smith 2000; Poe et al. 2002; Frew et al. 2003; Venkatachalam 2004; Whynes et al. 2005).

A particular factor which contributes to noisy or even biased measurements of WTP is preference uncertainty. Preference uncertainty may be caused by incomplete knowledge about the features of the object under evaluation or simply by the fact that a person is unsure about her own preferences (March 1978; Ariely et al. 2003; Gregory et al. 1993; Jacowitz and Kahnemann 1995; Shaikh et al. 2007). Since individuals are typically unable to gain experience of non-market goods through repeated purchase and consumption, preference uncertainty is highly relevant for CV studies (Dubourg et al. 1997). Due to vagueness of preference, people often have only regions of indifference instead of well-defined indifference curves (Loomes 1988; Butler and Loomes 2007; 2011; Cubitt et al. 2015), a fact that theoretically contradicts the existence of a single Point-WTP (Dost and Wilken 2012; Hanley et al. 2009; Wang et al. 2007).

Several CV studies based on closed-ended surveys take preference uncertainty into account. Ready et al. (1995), for example, allow for six response categories in their survey ranging from 'definitely yes' to 'definitely no'. Welsh and Poe (1998) apply a similar approach. Li and Mattsson (1995) and

Champ et al. (1997) allow respondents to express their uncertainty on scales from 0% to 100% or from 1 to 10. However, all these approaches involve several problems. All respondents must interpret the employed scales in the same way and be able to assess their degree of preference uncertainty correctly (Loomis and Ekstrand 1998; Hakansson 2008). Moreover, it is not at all clear how to interpret the obtained information. For instance Hakansson (2008) argues that the statement to be 60% certain to pay US\$100 for a given project should not necessarily be treated as an average WTP of US\$60. As response to this critique, several studies have addressed preference uncertainty by using payment cards to elicit lower (the maximum amount the individual is sure to be willing to pay) and upper (the minimum amount above the individual is sure to refuse to pay) bounds of WTP (Dubourg et al. 1997; Broberg and Brannlund 2008; Ellingson et al. 2009; Hanley et al. 2009; Mentzakis et al. 2010; Mahieu et al. 2012; Voltaire et al. 2013). The length of the interval between lower and upper bound can be regarded as a measure of preference uncertainty in these studies. However, the above mentioned general problems of closed-ended approaches, in particular the starting point and range biases remain.

The only open-ended CV study which addresses preference uncertainty has been performed by Hakansson (2008). The design of Hakansson allows respondents to state either an exact amount or an interval of two amounts as their WTP. The interval is elicited by responses to the statement 'I am willing to pay between ... and ...'. This means that the bounds of the interval are not clearly defined as lower (upper) bound of WTP, i.e. the maximum (minimum) amount for which the individual is sure to (refuses to) pay as in the closed-ended studies mentioned above. Consequently, respondents could differ in the interpretation of the interval bounds and also in the degree of uncertainty at which they switch from stating an exact amount to giving an interval. Nevertheless, the work of Hakansson (2008) led to rather promising results.

Recently, a new open-ended WTP elicitation approach was introduced in the marketing literature (Wang et al., 2007; Dost and Wilkens, 2012). Therein, WTP is elicited as a range with properly defined bounds as in the previous closed-ended studies. We call this approach Range-WTP in comparison to the traditional open-ended Point-WTP where only a single value is elicited. Until now, this method has been only used for the valuation of market goods, i.e. chocolate and wine. Our first goal is to apply the Range-WTP to CV studies for the valuation of non-market goods. While Wang et al. (2007) show that the Range-WTP outperforms the Point-WTP for predicting purchase probabilities of consumer goods, it is still unclear whether this holds also for our study since preference uncertainty is supposedly much larger for non-market goods. Our second goal is to compare the performance of Range- and Point- WTP for CV studies. In doing so, we use the criterion of theoretical validity of Range-WTP and compare it to that of Point-WTP. Therefore, we measure the degree to which WTP values are consistent with theoretical expectations. More precisely, we measure other subjective evaluations of our non-market good and test whether they are related to WTP measures in a consistent way (see section 3.3 for details). We also

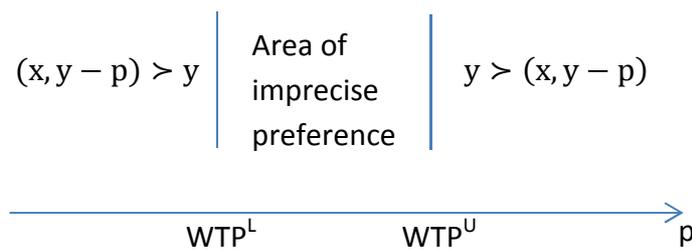
check for the stability of our results over time. In addition, we analyse the test-retest reliability by considering the correlation between the same respondents' answers at two different points in time. In a broader sense we want to contribute to the issue whether the earlier criticism on open-ended methods can be watered down by eliciting ranges. To the best of our knowledge, no previous paper has compared theoretical validity of two open-ended methods. Our third goal is to provide empirical evidence for our test case, the avoidance of the use of solar radiation management (SRM), a climate engineering technique that aims to counteract climate change by the injection of sulphate aerosols into the stratosphere (Royal Society 2009; Klepper and Rickels 2014). Apart from mitigation of carbon emissions, SRM has been discussed as an option for achieving the two-degree climate target. Since most people have never heard of SRM (see e.g., Merk et al. 2015; Mercer et al. 2011), preference uncertainty should be rather high for SRM. This is ideal for testing the performance of Range-WTP.

To compare the theoretical validity of Range- and Point-WTP, we conducted two large online surveys on SRM in Germany with a total number of nearly 1,500 participants. Both surveys were identically structured and all respondents received the same information before stating their preferences. However, in Survey A we elicited Point-WTP whereas in Survey B we elicited Range-WTP. This provides for an adequate comparison of response differences. To test for the stability of our results over time and for the test-retest reliability of both methods, we conducted a follow-up study in which about 800 of the initial 1,500 respondents participated.

The remainder of the paper is organized as follows: Section 2 introduces our conceptual framework and provides an overview of the elicitation approach. Section 3 outlines our data and survey design (3.1), WTP elicitation in more detail (3.2) and the test of validity and reliability (3.3). Section 4 discusses the results and section 5 concludes.

2. Conceptual framework

As argued above, asking for single Point-WTP may not be justified in the case of preference uncertainty, i.e. if well-defined indifference curves do not exist. To see this formally, consider a person with initial wealth y who is thinking about buying good x . Obviously, she will buy the good for price p if $(x, y-p) \succ y$, where \succ is the asymmetric part of her binary preference relation. In the case of thick indifference curves, the Point-WTP implicitly given by $(x, y - \text{WTP}) \sim y$ may not be well-defined. However, there exist an upper (WTP^U) and lower (WTP^L) bound of WTP defined by $\text{WTP}^U = \inf\{p \mid y \succ (x, y - p)\}$ and $\text{WTP}^L = \sup\{p \mid (x, y - p) \succ y\}$, see Figure 1. If preferences are continuous, i.e. if indifference curves are thin, the area of imprecise preferences will collapse such that $\text{WTP}^U = \text{WTP}^L = \text{Point-WTP}$.

Figure 1: Imprecise preferences

Wang et al. (2007) were the first to develop an open-ended approach where WTP is measured as the range between WTP^L and WTP^U rather than as a point. In a set-up involving 175 customers, they test the range approach in an experimental elicitation of consumers' reservation prices for chocolate and red wine. They assume linear decreasing purchase probabilities between the lower bound (100%), indifference range (50%) and upper bound (0%). A lottery ensures incentive compatibility, e.g., if the randomly drawn lottery price is lower than the lower bound, then the respondent must buy the good at the drawn lottery price. They conclude that Range-WTP yields better predictions for actual buying probabilities than Point-WTP. Dost and Wilken (2012) build on the Wang et al. (2007) approach but drop the elicitation of an indifference point and restrict the assumption of linear decreasing purchase probabilities. They test the range on a study of caffè latte and show that the traditional Point-WTP approach reveals the midpoint of the range. The only non-market CV study is Hakansson (2008). Hakansson (2008) elicits the WTP for increasing the number of wild salmon in a Swedish river. She proposes a similar approach though, as pointed out above, the interval bounds in her study are not clearly defined as WTP^L and WTP^U .

Our approach redefines, applies and tests the Range-WTP method proposed by Wang et al. (2007). Building on their initial approach, we ask respondents to provide a lower-bound WTP and an upper-bound WTP. Logic suggests that the upper bound should be identical to or exceed the lower bound of WTP. Unlike Wang et al. (2007), we apply the Range-WTP method to a public good rather than to consumer goods such as chocolate or red wine. We follow Dost and Wilken (2012) and drop the elicitation of an indifference price. We do not incentivise respondents and abstain from use of a lottery. This ensures that the method is survey-compatible and easy to understand for survey respondents. While Wang et al. (2007) show that Range-WTP is a better predictor of actual purchase probabilities for consumer goods as compared to Point-WTP, it remains an open question whether the range method is suitable for CV studies on non-market goods. This is particularly true as the marketing studies have applied the range method only to goods with very low preference uncertainty (chocolate, wine, coffee) while for our good (SRM) preference uncertainty should be rather high.

In order to investigate the suitability of Range-WTP for CV studies, theoretical validity, test-retest reliability and stability of results over time are important criteria. Theoretical validity can be defined as

the degree to which the empirical findings are consistent with theoretical expectations (Mitchell and Carson 1989). A number of existing studies compare the theoretical validity of different evaluation measures for environmental goods (e.g., Whitehead et al. 1998; Lienhoop and Ansmann 2011; Akter and Bennet 2013). Closely related to our study are Bateman et al. (1994; 1995), who in a study on national parks in the UK compare the theoretical validity of Point-WTP with that of the iterative bidding approach. The authors find that in line with theoretical expectations, the values elicited by Point-WTP are determined by a number of socio-economic factors such as income. Accordingly, they conclude that Point-WTP fulfils the criterion of theoretical validity. By contrast, Ressurreicao et al. (2011) find that in their study on species loss in the open sea Point-WTP does not fulfil the criterion of theoretical validity. The authors show that in terms of theoretical validity the closed-ended payment card method outperforms the Point-WTP method. Ressurreicao et al. (2011) argue that the Point-WTP method may not be suitable for more complex issues. Unlike our paper, these and other existing studies compare the traditional open-ended Point-WTP method with a closed-ended method.

As far as we know, no study has yet compared the theoretical validity of two open-ended methods, as we do in this paper by comparing the open-ended Point-WTP method with the open-ended Range-WTP method. Nor are we aware of any studies that have analysed whether results concerning theoretical validity are stable over time. We also investigate the test-retest reliability of the Range- and Point-WTP methods. Test-retest reliability of WTP measures is defined as the correlation between responses measured at different points in time with the same sample (Jorgensen et al. 2004) and has been addressed in several previous CV studies (e.g., Kealy et al. 1990; Loomis 1990).

3. Methodology and data

3.1 Data and survey design

Our study uses novel data from two surveys of representative internet users on SRM that we conducted in July 2014 and in August 2013 with two follow-up surveys in August 2014. The surveys were structured identically and differed only with respect to the WTP elicitation method. In Survey A, conducted in July 2014, WTP was elicited using the Point-WTP method. In Survey B, conducted in August 2013, WTP was elicited using the Range-WTP method. Our working samples consist of 776 (Survey A) and 663 (Survey B) observations. In the two follow-up studies conducted in August 2014 (referred to as Surveys A* and B*), we repeated Survey A and B with a subset of original respondents (468 and 303 respectively). All respondents aged 18 or above were recruited via a professional online panel. They were sampled using quotas for gender, age and place of residence (federal state).

The surveys were structured as follows: First, all respondents were asked about the current level of their SRM awareness. Then they were all shown the same information video about SRM. The video provided respondents with information on SRM using animated graphics. The animations were

supported by verbal explanations spoken by a professional radio presenter. Respondents who were not able to listen to or to play the video were excluded at the beginning of the survey. It was not possible to fast-forward the video or skip parts of it. The video first provided respondents with information on anthropogenic climate change and its likely consequences and explained the two-degree target. The video then introduced mitigation, adaptation and SRM as three possibilities of tackling climate change. Subsequently, the video explained SRM in more detail, i.e. its underlying mechanisms and its impact on climate change, the current state of research and the potential benefits and risks of SRM. The information was based on peer-reviewed papers and scientific reports (taken from, e.g., Crutzen 2006; IPCC 2007; IPCC 2012; Royal Society 2009). External experts checked the information for correctness and clarity. An English translation of the German video script is provided in the appendix. After watching the video, we asked respondents about the clarity of the information provided on the video. For each survey, more than 98% of the respondents indicated that they had understood the video well or very well.

After this initial information stage on the subject of SRM, we proceeded to elicit the respondents' acceptance of SRM. Respondents were asked about their level of agreement (or otherwise) 'to using SRM to counteract climate change'. Potential answers ranged from 1 ('strongly disagree') to 4 ('strongly agree'). Next, respondents were asked to assess the risks and benefits of SRM using a scale from 1 ('very small') to 4 ('very large'). Subsequently, we elicited respondents' WTP, using either the Point-WTP method (Survey A) or the Range-WTP method (Survey B). The WTP questions are described in more detail in section 3.2. We then elicited respondents' emotional response to SRM. Respondents were asked how strongly they experienced various positive reactions (delight, satisfaction, hopefulness, relief) and negative responses (worry, fear, sadness, anger, annoyance) when thinking about SRM, using a scale from 1 ('not at all') to 4 ('strongly'). In our analysis, we summarised negative and positive emotions in a composite index. Finally, we collected information on the respondents' gender, age, income and education. A respondent with a higher-education entrance certificate is coded as having a high level of education.

Table A-1 in the appendix contains summary statistics for all survey items used in our analysis.

3.2 Willingness to pay elicitation

In both surveys, respondents were first asked to consider a hypothetical situation in which there were two potential ways of achieving the two-degree target, one being SRM, the other increased investment in renewable energy and improvement of energy efficiency (EE). Respondents were then asked whether they would prefer SRM or EE as a way of achieving the two-degree target. 'Don't know' answers were also possible. Respondents thus first expressed their preferences for or against using SRM. In a follow-up question, respondents were then asked to assume that their chosen option would be more costly to

realise than the alternative option. If, for instance, a respondent chose EE, we asked her to assume that it would be more costly to reach the two-degree target via EE than via SRM. Respondents were then asked to state their WTP either for the avoidance of SRM via EE (if they chose EE) or for the avoidance of EE via SRM (if they chose SRM). For the exact wording of the questions, see table A-2 in the appendix.

In Survey A we elicit Point-WTP. Taking the example of a respondent who chose EE over SRM, we asked her to state the maximum amount of money she would be willing to pay each month for the avoidance of SRM via EE. In Survey B, by contrast, we elicit Range-WTP. Respondents were asked to state a lower and an upper bound of WTP. Taking the same example of a respondent who chose EE over SRM, the lower bound of Range-WTP was elicited by asking the respondent to state the monthly amount of money that she would definitely be willing to pay to ensure avoidance of SRM via EE. The upper bound was elicited by asking the respondent to state the monthly payment at, or above, which she would definitely no longer prefer EE to SRM. We refer to the averages of the lower and upper WTP bounds as Range-WTP.

Regarding stated WTP values, our analysis considers only WTP values that are non-negative and smaller than EUR 500. Values above EUR 500 Euro were winsorised by setting them equal to EUR 500. In literature, winsorising is a standard approach to curtailing the influence of outliers (see e.g., Kahnemann and Ritov 1994). Also, very high WTP values may simply reflect inaccurate answers or protest against the use of SRM. For Range-WTP we only consider WTP values if the stated value for the upper WTP bound is above the lower bound value. Finally, for respondents stating only one WTP value in the Range-WTP survey, we used this value as lower and upper bound, as it seemed legitimate to assume that those 12 respondents were certain about their preferences. However, excluding these observations leaves our results as described below unchanged.

3.3 Validity and reliability

We also compared and analysed the performance of the range and point methods with respect to theoretical validity and test-retest reliability. To address theoretical validity, we analyse whether the stated WTP values coincide and correlate with other objective or subjective factors. Logic suggests that these should be systematically related to the stated WTP values (Cai et al. 2010). In this way, we not only elicited respondents' WTP for the avoidance of SRM but also their self-reported acceptance of SRM, their risk perception for SRM and other perception measures. Obviously, these perception measures should be related to the respondents' WTP. For instance, respondents who disagree with the use of SRM or who perceive the risks of SRM as severe should display a higher WTP value for the avoidance of SRM. We further analyse the test-retest reliability of the two methods by considering the correlation between the same respondents' answers at two different points in time

(Jorgensen et al. 2004). Furthermore, we test whether our results on theoretical validity are stable over time (section 4.2.4).

4. Empirical findings

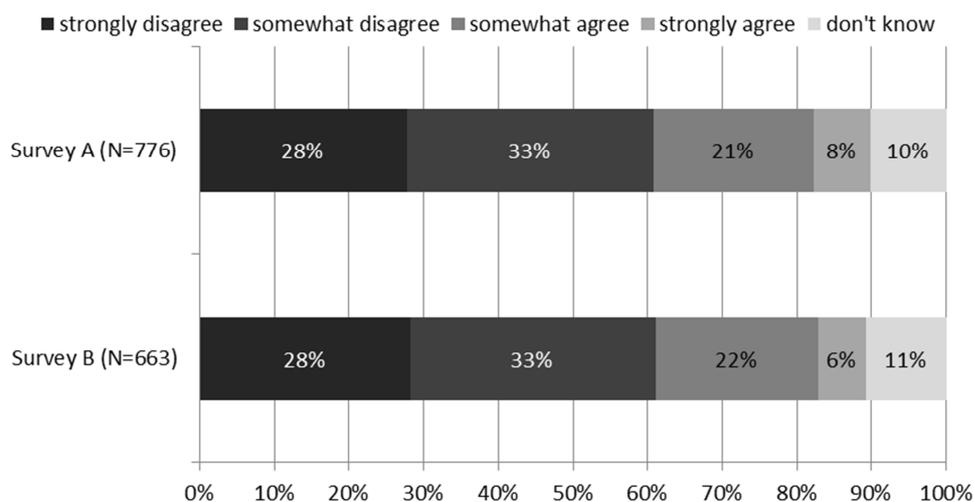
We first describe our findings on acceptance and WTP for the two surveys separately (section 4.1), proceeding from there to compare the theoretical validity of the two WTP methods (section 4.2). We start by analysing how the correlation with acceptance differs between the two WTP methods (section 4.2.1). We then extend our analysis and also consider the correlation of WTP values with other perception measures such as risk perception (section 4.2.2). In addition, we report robustness checks, where we also show that all our results are robust to changes in the threshold of the WTP values (section 4.2.3). Finally, we test whether our results on theoretical validity are stable over time (section 4.2.4).

In the following, we restrict our analysis to the overwhelming majority of respondents in both surveys who chose EE (86% in Survey A, 90% in Survey B). We refer to the averages of the lower and upper WTP bounds as Range-WTP.

4.1 Descriptive findings

Figure 2 illustrates our findings on the acceptance of SRM in the two surveys. In Survey A, 61% of all respondents stated that they disagreed either strongly or to some extent with the use of SRM to counteract climate change. By contrast, only 29% of the respondents agreed either somewhat or strongly with the use of SRM.

Figure 2: Acceptance of SRM in Survey A (Point-WTP) and Survey B (Range-WTP)



Note: The survey asked the following question: 'Please state your level of (dis)agreement with the following statement: We should use SRM to counteract climate change.'

The figures are almost identical for Survey B. Here, 61% of the respondents disagreed with the use of SRM and only a minority of 28% agreed. Overall, we find virtually identical levels of acceptance in the two surveys (Wilcoxon rank sum test $p=0.6930$). Moreover, the overwhelming majority in both surveys chose EE (86% in Survey A, 90% in Survey B) over SRM.

Up to this point, both surveys were exactly identical. In fact, we find almost identical levels of choice and acceptance of SRM in the two surveys. The results of the two surveys are, therefore, highly consistent. However, when we apply the two methods to eliciting the WTP of respondents and compare the WTP figures for both methods, we find major differences. For Survey A (Point-WTP) we find a mean WTP of EUR 44 for EE and a median WTP of EUR 20. Overall, 12% of the respondents reported a Point-WTP of zero. In Survey B (Range-WTP), we find that the mean of the lower bound WTP for EE is EUR 52 and the mean of the upper bound WTP value is EUR 126. The mean WTP value of the Range-WTP, the averages of the lower and upper WTP bounds, is EUR 89 (with a median of EUR 55). Here, 6% of the respondents reported a Range-WTP of zero.

Overall, we thus find that the stated WTP values differ greatly between Survey A and Survey B although the levels of acceptance do not. It is at first sight somewhat puzzling that the lower bound of Range-WTP exceeds Point-WTP. Wang et al. (2007) argue that the lower bound should be close to Point-WTP and for chocolate their lower bound is also larger than Point-WTP. In our study, differences may also be due to the time interval between both surveys, probably due to an increasing awareness of climate change. In fact, in the follow-up studies, which we report on in section 4.2.4, Point-WTP and lower bound are nearly identical. A potential explanation for why the lower bound is close to the Point-WTP is that respondents take the lower bound as a reference point for their valuations. The lower bound therefore acts as an anchor for determining the Point-WTP. There is ample evidence that there is insufficient adjustment in the case of anchoring (Whitehead et al. 1998). This implies in our case that the Point-WTP is close to the lower bound. However, in the present study we are not primarily interested in the absolute size of WTP measures but in their theoretical validity, which is what we analyse next.

4.2 Theoretical validity of willingness to pay measures

4.2.1 Acceptance and willingness to pay

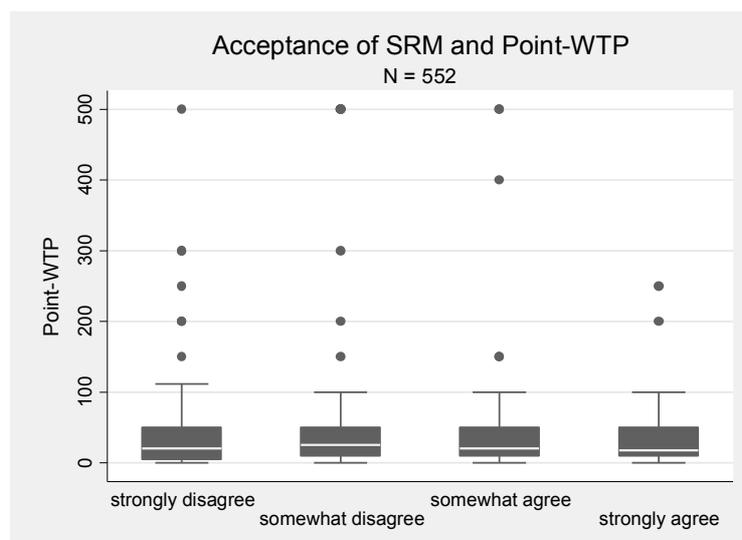
In a first step, we test whether the general decision to choose EE instead of SRM is negatively correlated with the acceptance of SRM. We expect a negative correlation: respondents who choose EE should also disagree with the use of SRM.

We find for both surveys that the choice of EE over SRM is strongly negatively correlated with the stated acceptance of SRM. The correlation is -0.4987 (p value of 0.0000) in Survey A and 0.4766 (p value of 0.0000) in Survey B. Therefore, as expected, respondents who disagree with the use of SRM also choose EE over SRM. This is true for both surveys, so the results of the surveys are again highly consistent.

In a second step, we then tested whether respondents who disagree (agree) strongly with using SRM to counteract climate change also revealed higher (lower) WTP for the avoidance of SRM. In the presence of theoretical validity, WTP for the avoidance of SRM should be negatively related with the acceptance of SRM. Surprisingly, we find that Point-WTP is not significantly correlated with acceptance. The correlation is low (0.0297) and insignificant, with a p value of 0.4868 . Using the Point-WTP method, we therefore find no evidence for the hypothesis that respondents who are less agreeable to using SRM also have higher WTP for the avoidance of SRM. Accordingly, the Point-WTP method does not seem to satisfy the theoretical validity criterion.

Further evidence comes from Figure 3, which visualises the relation between acceptance and Point-WTP in a boxplot diagram. Median WTP remains almost unchanged between the categories and is even the same for the categories of 'strongly disagree' and 'somewhat agree' (EUR 20). Theoretically, respondents who 'strongly disagree' with the use of SRM should state a higher WTP than respondents who 'somewhat agree' with its use. However, the boxplot diagram does not provide any evidence for this prediction. In fact, we find that median WTP is EUR 5 higher for those respondents who 'somewhat disagree' than for those who 'strongly disagree'. This finding again runs counter to theoretical expectations.

Figure 3: Boxplot diagram: Acceptance of SRM and Point-WTP (Survey A)

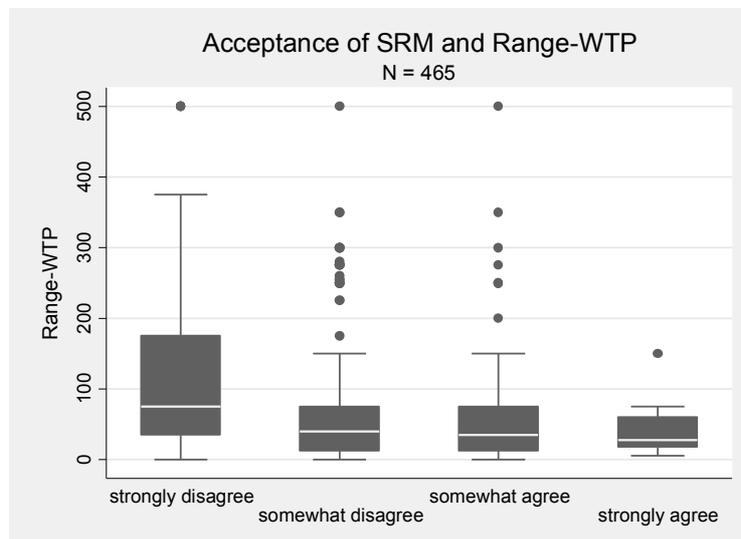


In contrast to our previous result, we find a strong and statistically significant negative correlation of -0.2438 (p value of 0.000) between acceptance and Range-WTP. We also find highly statistically

significant correlations between acceptance and the upper bound (correlation of -0.2637, p value of 0.0000) and lower bound (correlation of -0.1398, p value of 0.0025) of Range-WTP. Accordingly, respondents who reveal lower levels of acceptance are indeed willing to pay more for the avoidance of SRM via EE. Using Range-WTP, we therefore find evidence for the theoretical proposition that acceptance of SRM and WTP for the avoidance of SRM are negatively related.

Figure 4 shows that the median of Range-WTP decreases with higher levels of acceptance. Median Range-WTP is EUR 75 for those who ‘strongly disagree’ but only EUR 27.5 for those who ‘strongly agree’. Therefore, the median declines by almost EUR 50 as we move from the lowest to the highest acceptance category.

Figure 4: Boxplot diagram: Acceptance of SRM and Range-WTP (Survey B)



We also control for systematic differences in respondents’ socio-demographic characteristics and their level of awareness of SRM by analysing the theoretical validity of both measures for subgroups of the sample.

Our findings on the correlation between acceptance and WTP also hold for different subgroups of the sample (defined by awareness, i.e. whether respondents had heard or not heard about SRM before the time of our survey, gender, education, age and income). Table 1 summarises these findings. For all different subgroups, not only Range-WTP but also its lower and upper bound are statistically significantly correlated with acceptance (results not shown). There is only one exception. The correlation between the lower bound and acceptance is not statistically significant for respondents aged 49 or above. In sharp contrast to the findings for Range-WTP, Point-WTP is not correlated with acceptance for any subgroup.

In summary, we find that Range-WTP is highly correlated with acceptance. In terms of theoretical validity, Range-WTP thus seems to outperform Point-WTP, which is not correlated with acceptance at all.

Table 1: Correlation of acceptance and WTP

	Range-WTP	Point-WTP
All	-0.2438 *** (0.0000) N=465	0.0297 (0.4868) N=552
Awareness: No	-0.2120 *** (0.0001) N=355	0.0512 (0.2929) N=424
Awareness: Yes	-0.3216 *** (0.0006) N=110	-0.0226 (0.8003) N=128
Men	-0.2454 *** (0.0001) N=235	0.0110 (0.8465) N=312
Women	-0.2428 *** (0.0002) N=230	0.0588 (0.3645) N=240
Education not high	-0.2154 *** (0.0002) N=295	0.0748 (0.1627) N=350
Education high	-0.2954 *** (0.0001) N=170	-0.0455 (0.5199) N=202
Age <=49 years	-0.2955 *** (0.0000) N=247	0.0613 (0.3242) N=261
Age >49 years	-0.1935 *** (0.0041) N=218	-0.0048 (0.9347) N=291
Income <=2500 Euro	-0.2170 *** (0.0012) N=220	0.0792 (0.1786) N=290
Income > 2500 Euro	-0.2709 *** (0.0000) N=245	-0.0377 (0.5431) N=262

Note: p values in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4.2.2 Perception measures and willingness to pay

We have shown that acceptance is not correlated with Point-WTP but highly negatively correlated with Range-WTP. We now analyse whether these findings also hold for other perception measures, such as risk and benefit perceptions or emotions about SRM. Our expectation is that respondents who perceive the risks of SRM to be more severe or who are more concerned about the use of SRM will also be willing

to pay more for its avoidance. Table 2 shows how different perception measures are correlated with Range-WTP and Point-WTP.

Table 2: Correlation of perception measures and WTP

Perception measures	Range-WTP	Point-WTP
Risk perception	0.2169 *** (0.0000)	-0.0304 (0.4749)
Benefit perception	-0.1458 *** (0.0018)	0.0184 (0.6677)
Negative emotions	0.2280 *** (0.0000)	-0.0521 (0.2134)
Positive emotions	-0.1516 *** (0.0009)	0.0539 (0.1998)

Note: P values in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Again we find that, in terms of theoretical validity, Range-WTP performs much better than Point-WTP. Point-WTP is not correlated with any of the perception measures. By contrast, Range-WTP is significantly correlated with all perception measures. Range-WTP is, for instance, positively correlated with respondents' risk perception. Respondents who perceive the risks of SRM to be appreciably severe are also willing to pay more for the avoidance of SRM. We also find a statistically significant positive correlation between Range-WTP and negative emotions towards SRM. Respondents who are concerned, angry or anxious display a higher WTP for the avoidance of SRM via EE. Also, the lower and upper bound of Range-WTP are statistically significantly correlated with all other perception measures (results not shown). There is only one exception. The correlation between the lower bound and benefit perception is not significant. Importantly, we find these relations only for Range-WTP and not for Point-WTP. The results strengthen our conclusion that the range method clearly outperforms the point method in terms of theoretical validity.

4.2.3 Robustness

As robustness check, we have set the threshold of EUR 500 to EUR 200 and winsorised the data by setting all WTP values of more than 200 to the upper bound of 200. Also, instead of winsorising the data to a certain threshold, we excluded all observations with WTP values of more than EUR 500 (200). Finally, we also excluded values above the 95th percentile. In all cases our results remain qualitatively unchanged. Details are available upon request.

4.2.4 Reliability and stability

In a follow-up surveys, we investigated whether our results were reliable and stable over time. First, we analysed the test-retest reliability of the two methods. To do so, we analysed the correlation between

the same respondents' WTP at two different points in time. Second, we checked whether our results on the theoretical validity of the WTP methods were stable over time. For these purposes, we repeated both surveys in August 2014 and again asked the respondents to state their acceptance and WTP. Overall, 468 of the original respondents participated in follow-up Survey A* (60%) and 303 in follow-up Survey B* (46%).¹⁰ As with the original surveys, both follow-up surveys were structured identically and differed only with respect to the WTP elicitation method. In follow-up Survey A*, respondents were again asked to state the Point-WTP, whereas in follow-up Survey B* respondents were again asked to state the Range-WTP.¹¹

For both surveys, we find that WTP decreased over time. In follow-up Survey A*, the mean of the Point-WTP is EUR 32 (with a median of EUR 20) and is, therefore, almost EUR 12 lower than in the initial Survey A. In follow-up Survey B*, the mean of the Range-WTP is EUR 65 (with a median of EUR 35, a lower bound of EUR 33 and an upper bound of EUR 97) and is therefore EUR 24 lower than in the initial Survey B. Interestingly, the lower bound of the Range-WTP and the Point-WTP are now, as in the studies of Wang et al. (2007), almost identical. The somewhat larger difference between the lower bound and the Point-WTP in the initial surveys may, therefore, indeed be due to the time interval between the initial Surveys A and B.

If we restrict the sample of the initial Surveys A and B to those respondents who participated in the follow-up survey, we also find a decrease in WTP. In fact, the mean Point-WTP for the restricted sample of the initial Survey A is EUR 43 and is, therefore, almost identical to the mean Point-WTP for the complete sample of the initial Survey A (mean Point-WTP of EUR 44). The mean Range-WTP for the restricted sample of the initial Survey B is EUR 87 (with a lower bound of EUR 48 and an upper bound of EUR 126) and is, therefore, also almost identical to the mean Range-WTP for the complete sample of the initial Survey B (mean Range-WTP EUR 89, with a lower bound of EUR 52 and an upper bound of EUR 126).

Analysing the test-retest reliability of the two methods, we find for both methods a high and statistically significant correlation between the WTP values over time (Point-WTP: correlation of 0.4469, p value of 0.0000; Range-WTP: correlation of 0.4240, p value of 0.0000). Therefore both methods fulfil the criterion of test-retest reliability.

¹⁰ Note that the time difference between Survey A and its follow-up Survey A* is one year, whereas the time difference between Survey B and its follow-up Survey B* is one month. However, we do not expect the length of the time difference to influence the reliability and stability of our results. The time length should have a similar effect on both measures, WTP value and acceptance, so that the correlation between the two remains stable.

¹¹ Overall, 17 respondents who chose EE in Survey A chose SRM in Survey A*. In Survey B*, 31 respondents who had previously chosen EE chose SRM. Excluding these respondents from our analysis does not affect our results presented in the previous sections.

Analysing the stability of our results over time, the two follow-up surveys confirm our previous results on the theoretical validity of the two WTP methods. For follow-up Survey A*, we find that the correlation between acceptance and Point-WTP is small (0.0095) and statistically insignificant (p value of 0.8621). Accordingly, the Point-WTP again fails to satisfy the criterion of theoretical validity. For follow-up Survey B*, by contrast, we find that the correlation between acceptance and Range-WTP is strong (-0.2036) and highly statistically significant (p value of 0.0042). If we restrict the initial samples of Survey A and Survey B to those respondents that participated in the follow-up survey, the above results are confirmed. We find no statistically significant correlation between acceptance and Point-WTP (p value of 0.6949) but a highly statistically significant correlation for Range-WTP (p value of 0.0002).

Table 3 shows how different perception measures are correlated with Range-WTP and Point-WTP for the follow-up surveys A* and B*. Again we find that, in terms of stability of theoretical validity over time, Range-WTP performs better than Point-WTP. Range-WTP is significantly correlated with all perception measures except for positive emotions. In contrast, Point-WTP is correlated with negative emotions, but is uncorrelated with risk and benefit perception and it even reveals the wrong sign for positive emotions.

Table 3: Correlation of perception measures and WTP

Perception measures	Range-WTP Survey A*	Point-WTP Survey B*
Risk perception	0.2530*** (0.0005)	0.0482 (0.3742)
Benefit perception	-0.1894 *** (0.0096)	0.0890 (0.1050)
Negative emotions	0.2493 *** (0.0003)	0.1054** (0.0440)
Positive emotions	-0.0814 (0.2422)	0.0873* (0.0953)

Note: P values in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Accordingly, Range-WTP also meets the criterion of theoretical validity in the follow-up survey, conducted a full year after the initial survey. This finding further strengthens our conclusion that the Range-WTP method clearly outperforms the Point-WTP method.

5. Discussion and conclusion

This paper compares two different open-ended methods of eliciting WTP. The first method, probably the most widely used method in practice, elicits WTP as a point. The second method elicits WTP as a range. One major criticism of the Point-WTP method is that it implicitly assumes that respondents know their preferences with certainty. Only under this assumption are they able to state one exact WTP value.

By contrast, the Range-WTP method allows for preference uncertainty: respondents are free to state a range of values.

We compare the performance of both methods using the criterion of theoretical validity. The specific case we consider is WTP for the avoidance of SRM via increased investment in renewable energy and an improvement in energy efficiency (EE). At present, SRM is a relatively little-known technique for counteracting climate change and we expect respondents to exhibit a high degree of preference uncertainty. To analyse the theoretical validity of the two WTP methods, we conducted two large scale surveys in Germany eliciting respondents' attitudes towards SRM and their WTP for the avoidance of SRM. The surveys were structured identically and differed only with respect to the respective WTP method. Survey A elicited WTP as a point, Survey B as a range. In two follow-up studies we repeated Survey A and B with the same set of respondents. We analysed the test-retest reliability of the two methods and studied whether the stated WTP values correlate over time. Furthermore, we analysed whether our results on the theoretical validity of the WTP methods were stable over time.

Our results are as follows: First, the stated WTP for the avoidance of SRM via EE differs strongly between the two surveys and thus depends on the WTP method used. Mean WTP elicited by the Point-WTP method is EUR 44, whereas mean Range-WTP is EUR 89. In contrast to Dost and Wilken (2012) we thus cannot find any evidence that the mean of the Range-WTP equals the Point-WTP. The main reason for this difference seems to be the fact that Dost and Wilken (2012) elicit valuations for a cup of coffee where, in sharp contrast to SRM, no preference uncertainties should be involved and market prices are known, i.e. where application of the range method seems limited. Nor did we find any evidence for the hypothesis mooted by Hakansson (2008), who argues that the lower and upper bounds may provide a kind of confidence interval for Point-WTP. Our follow-up surveys confirm notably the results by Wang et al. (2007), who find that the lower bound of Range-WTP is close to Point-WTP.

Second, we find a strong and statistically significant negative correlation between acceptance of SRM and Range-WTP. Respondents who disagree (agree) strongly with the use of SRM to counteract climate change also display a high (low) WTP for the avoidance of SRM. Accordingly, Range-WTP fulfils the criterion of theoretical validity. By contrast, acceptance and Point-WTP are uncorrelated. Therefore, the Point-WTP method does not meet the criterion of theoretical validity. Third, comparing the original with the follow-up surveys, we find that both methods fulfil the test-retest reliability criterion, since WTP values are highly correlated over both elicitation. Fourth, we show that the statistically significant negative correlation between acceptance and Range-WTP remains stable over time.

SRM is a relatively new technique that has hitherto been mostly discussed by experts and is largely unknown to the broader public. Yet the traditional Point-WTP method requires that respondents know their preferences with certainty and that they are familiar with the good in question so as to ensure that

the elicited WTP values are reliable and valid (Mitchell and Carson 1989). By contrast, the Range-WTP method allows for preference uncertainty as it elicits more information about respondents' preferences. While uncertain respondents are free to state a range of values, respondents who are certain about their preferences can also state equal lower and upper bounds. Therefore the range provides more information on respondents' preferences than a single point. In our application, the upper bound of the range shows the strongest correlation with acceptance.

Our results support earlier criticism of the traditional open-ended Point-WTP method. We put forward and test an alternative open-ended approach, the Range-WTP method, which addresses this criticism. Given the increasing evidence on distortions induced by the use of closed-ended methods (i.e. starting point, range, and yea-saying biases) we believe that our results provide strong reasons to revive the interest in open-ended methods. Besides the richer set of information on individual preferences provided by open-ended methods they also have advantages for studies devoted to more than one country (Bateman et al. 2005; Hakansson 2008). Preference uncertainty could be regarded as one major reason for the poor empirical performance of open-ended Point-WTP; Range-WTP, at least in our studies, improves measurement substantially. Given these results, an important route for future research is to compare the performance of open- and closed-ended elicitation of WTP intervals.

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7. Appendix

Table A-1: Summary statistics

<i>Variables</i>	<i>Domain</i>	<i>Survey A</i>		<i>Survey B</i>	
		<i>mean</i>	<i>standard deviation</i>	<i>mean</i>	<i>standard deviation</i>
Awareness	0 (have never heard); 1 (have heard at least a little bit)	0.19	0.39	0.23	0.42
Acceptance	1 (strongly disagree) – 4 (strongly agree)	2.09	0.93	2.07	0.91
Risk perception	1 (very small) – 4 (very large)	3.23	0.74	3.29	0.74
Benefit perception	1 (very small) – 4 (very large)	2.45	0.78	2.43	0.77
Emotions (negative)*	1 (not at all) – 4 (strongly)	0.002	0.81	0.002	0.81
Emotions (positive)*	1 (not at all) – 4 (strongly)	-0.007	0.88	0.003	0.91
Gender	0 (male); 1 (female)	47%		51%	
High education	0 (other); 1 (A level)	34%		34%	
Income (monthly household income in €, net of taxes)	250 – 10,000	2400.47	1565.56	2483.25	1478.38
Age	18 – 87	47	15.42	46	15.21
N		776		663	

Note: * Mean values for emotions are averages of standardised items (mean = 0, standard deviation = 1). Items for negative emotions include worry, fear, sadness, anger, annoyance. Items for positive emotion encompass delight, satisfaction, hopefulness, relief.

Table A-2: Willingness to pay questions

Introductory question

Please consider the following situation:

Assume that the two-degree target is to be met. The international community sees two options for achieving the two-degree target:

1. Use of solar radiation management (SRM)
2. Reinforced expansion of renewable energies and improvement of energy efficiency (EE)

Assume first that, independently of the actual costs, both options would be equally costly. Which option would you prefer for achieving the two-degree target?

- Solar radiation management (SRM)
- Reinforced expansion of renewable energies and improvement of energy efficiency (EE)
- Don't know

Survey A: Point-WTP question

(If the respondent chose EE in response to the introductory question)

Assume now that *reinforced expansion of renewable energies and improvement of energy efficiency (EE)* costs more than *solar radiation management (SRM)* and that EE would involve monthly costs for you.

Please answer the question assuming that you would actually have to pay the amount each month in addition to your monthly ongoing expenses for accommodation, accessory charges, daily needs and further purchases.

What is the maximum amount of money you would be willing to pay each month in order to achieve the two-degree target via reinforced expansion of renewable energies and improvement of energy efficiency (EE) rather than the use of SRM?

Please state the maximum amount here:

EUR _____

Survey A: Point-WTP question

(If the respondent chose SRM in response to the introductory question)

Assume now that *solar radiation management (SRM)* costs more than *reinforced expansion of renewable energies and improvement of energy efficiency (EE)* and that the use of SRM would involve monthly costs for you.

Please answer the question assuming that you would actually have to pay the amount each month in addition to your monthly ongoing expenses for accommodation, accessory charges, daily needs and further purchases.

What is the maximum amount of money you would be willing to pay each month in order to achieve the two-degree target via the use of solar radiation management (SRM) rather than EE?

Please state the maximum amount here:

EUR _____

Survey B: Range-WTP question: (if the respondent chose EE in response to the introductory question)

Assume now that *reinforced expansion of renewable energies and improvement of energy efficiency (EE)* costs more than *solar radiation management (SRM)* and that EE would involve monthly costs for you.

Please answer the question assuming that you would actually have to pay the amount each month in addition to your ongoing monthly expenses for accommodation, accessory charges, daily needs and further purchases.

Up to which level of costs for yourself would you definitely choose EE?

EUR _____

At or above which level of costs for yourself would you definitely no longer choose EE but SRM?

EUR _____

Survey B: Range-WTP question: (if the respondent chose SRM in response to the introductory question)

Assume now that *solar radiation management (SRM)* costs more than *reinforced expansion of renewable energies and improvement of energy efficiency (EE)* and that the use of SRM would involve monthly costs for you.

Please answer the question assuming that you would actually have to pay the amount each month in addition to your ongoing monthly expenses for accommodation, accessory charges, daily needs and further purchases.

Up to which level of costs for yourself would you definitely choose SRM?

EUR _____

At or above which level of costs for yourself would you definitely no longer choose SRM but EE?

EUR _____

Information provided in the SRM video

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere (e.g., CO₂) ensure that some of this warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals and plants to live on.

Since the start of industrialisation around 1850, people have emitted a very large amount of greenhouse gases by burning coal, oil and gas. These gases trap more heat in the atmosphere and cause a gradual increase in average global temperature.

Since 1900, global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in average global temperature should not exceed two degrees compared to pre-industrial levels. The attempt to ensure that this is the case is referred to as the two-degree target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To achieve the two-degree target, the current level of emissions would have to be cut by more than half by 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of severe precipitation events in many regions. It is likely that in future more areas will be affected by extended droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the CO₂ emitted is absorbed by the ocean, thus causing ocean acidification.

There are different ways of dealing with climate change.

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is to reduce global temperature by means of solar radiation management (SRM).

Via SRM some sunlight is reflected before it can warm the Earth. This can be accomplished by, for example, spraying sulphate particles into the atmosphere at a high altitude.

A similar phenomenon can be observed in nature. When large volcanoes erupt, similar particles are distributed across wide areas of the Earth's atmosphere, cooling the Earth.

The particles remain in the higher regions of the atmosphere for approximately two years. To prevent the Earth from heating up again, spraying would have to be continued until the cause of global warming

has been removed. Because CO₂ remains in the atmosphere for a very long time, SRM might have to be used for several centuries. However, using SRM will not stop ocean acidification.

Currently, the risks, benefits and feasibility of SRM are the object of research.

The use of SRM entails benefits as well as risks. One of the benefits is that it would be a quicker way of counteracting global warming than cutting down on greenhouse gas emissions. This would buy additional time to remove the cause of climate change, i.e., the high concentration of greenhouse gases in the atmosphere. Massive and irreversible changes in the climate could be stopped before too much damage has been done. Furthermore, it would be possible to stop climate change even if certain countries decide not to reduce their greenhouse gas emissions. Deploying SRM would be less expensive than reducing the consumption of fossil fuels.

The risks include a change in the amount of precipitation in most regions. Arid regions in particular would have to cope with even less rain. If the deployment of SRM were suddenly stopped, global temperature would rise abruptly. The speed of this rise in temperature would lead to severe problems for humans and the environment. Because possible side effects would be trans-boundary, the use of SRM could cause international conflicts. Once in use, SRM might have a negative effect on people's motivation to change their lifestyle: greenhouse gas emissions would continue to increase. Other hitherto unknown and unforeseeable risks might also arise.

Paper III: Informed and uninformed opinions on new measures to address climate change

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Abstract

Climate engineering (CE) and carbon capture and storage (CCS) are currently controversially debated options to address climate change. Our paper provides empirical evidence on the public perception of two different CE measures, namely, on solar radiation management via stratospheric sulphate injection (SRM) and afforestation, as well as CCS. Using data from a novel large-scale survey, we analyse the determinants of acceptance of these measures in Germany. We also provide experimental evidence on how additional information on these measures changes the respondents' acceptance. We show that the acceptance differs strongly between the three measures. Afforestation is strongly favoured over CCS and SRM. This ranking holds independent of the amount of information provided. For all three measures, we find that, on average, additional information decreases acceptance. However, the sign and the strength of the information effect strongly depend on personal characteristics, such as gender and risk attitude.

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1. Introduction

Most countries have accepted a temperature increase of 2°C above pre-industrial levels as the maximum tolerable limit for global warming. Reaching this 2°C target, however, becomes increasingly unlikely given the current trajectories (IPCC 2014). Therefore, scientists and politicians have recently begun to consider new measures to address climate change. These measures involve large-scale interventions into the climate system and have been summarised under the term climate engineering (CE). CE encompasses two broad approaches: solar radiation management (SRM) and carbon dioxide removal (CDR) (Royal Society 2009). While SRM measures influence the temperature directly, CDR measures reduce the atmospheric concentration of CO₂. Another relatively new measure is carbon capture and storage (CCS). For CCS, CO₂ from industrial processes is captured before it enters the atmosphere and is transported to long-term storage.

The costs, benefits, and risks of these new measures, especially CE, currently are not well understood, and uncertainties remain regarding their effectiveness and side effects (Royal Society 2009; UBA 2008; Keith 2014). While research on most CE measures is still at an early stage, there are already large-scale demonstration projects on CCS. Further research on CE measures and CCS must be conducted before it can be determined whether they could become part of a portfolio to address climate change. However, in some countries even limited field research on CE and CCS is often met with widespread public protests. For instance, a small scale field experiment on ocean iron fertilisation—a CDR measure—in the South Atlantic created considerable protest among the German public. Consequently, the German Federal Ministry for the Environment called for an immediate stop of the experiment.¹² Several CCS demonstration projects in Germany faced strong opposition from both the public and local politicians (Dütschke 2010). In some instances, the explorations have been stopped entirely because of public protests.¹³ These examples show that public acceptance will crucially determine the future of CE and CCS. It is an open question, however, whether the public protests have been mainly caused by a lack of information about the new measures or, the other way around, whether more information would lead to even stronger opposition. Informing the public and taking into account its concerns may thus have a strong impact on acceptance.

Our paper contributes to the literature by focusing on people's perception of these new measures to address climate change. More specifically, our paper addresses the following research questions: (1) How does the public perceive different measures? (2) How does the acceptance of the measures differ between uninformed and informed respondents? (3) How do personal characteristics influence the perception of the measures, and (4) can personal characteristics explain differences in the acceptance

¹² http://www.bmbf.de/_media/press/Univ_Heidelberg_zu_LOHAFEX.pdf, 31.07.2015

¹³ <http://www.iea.org/media/workshops/2011/ccstalk/Fischer.pdf>, 31.07.2015

between uninformed and informed respondents? As will become apparent from the literature review (section 2 below) studies exist that investigate these questions with different degrees of correspondence. However, to the best of our knowledge, no study exists that is able to compare people's perception for all three measures (SRM, CDR and CCS) within a consistent framework. This is particularly important given the potential differences in the direction and the magnitude of the effect of information between the measures.

To address these questions, we conducted a large online experiment with more than 3500 participants in Germany. Compared to other Europeans, Germans express more negative attitudes toward nuclear energy and CCS but more positive attitudes toward wind and hydroelectric energy (European Commission 2011). This makes Germany an especially interesting case for further analyses on other risky technologies. We elicit the perceptions of a heterogeneous set of three measures (research question 1). The first measure is stratospheric sulphate injection. It is a SRM measure where sulphate is injected at a high altitude to block part of the incoming sunlight and thus reduces the global temperature. For simplicity we will refer to this technology as SRM. The second measure is large-scale afforestation, a CDR measure where large areas like the Sahara and the Australian Outback are afforested. The third measure is carbon capture and storage. All measures differ with respect to their expected effectiveness, expected side effects and the uncertainty about both.

To determine the effect of additional information (research question 2), we experimentally varied the amount of information our respondents received. The control group received only basic information (BI), whereas the treatment group received full information (FI) on a measure. We also test for the effect of personal characteristics on the acceptance (research question 3) and for the interaction of the treatment effect of additional information with personal characteristics (research question 4).

The remainder of the paper is structured as follows. Section 2 surveys the previous literature and relates it to our research questions. Section 3 outlines the survey design and the data while the methodological approach is presented in section 4. The results of our empirical analysis are described in section 5. Section 6 discusses and concludes.

2. Literature review

Most of the related studies have investigated the above research questions individually. For this reason our literature review presents their findings by research question.

Systematic evidence on research question (1), i.e., the measures' public perception, is still relatively scarce, and most studies focus on only one measure. The existing literature includes studies based on focus group and Delphi studies on the one hand, and more often opinion polls and surveys on the other hand (see Bellamy et al. 2012 and Scheer and Renn 2014 for a recent overview).

Among the three measures we look at, the perception of CCS is the most thoroughly researched thus far. Respondents from a broad range of countries are often either sceptical or undecided about CCS (e.g., Curry 2004; Duan 2010; Itaoka et al. 2012; Krause et al. 2014; Miller et al. 2008). The studies, however, show considerable variation, which is most likely due to different national contexts, the specific storage location or the information respondents receive. Studies on SRM report generally low levels of acceptance (Mercer et al. 2011; Merk et al. 2015; Sugiyama and Fujiwara 2012). Studies on afforestation report generally high levels of acceptance (Curry et al. 2005; Lin et al. 2012).

A few studies exist that compare attitudes across measures. Royal Society (2009) and IPSOS Mori (2010) find evidence that public attitudes differ between CDR and SRM measures, with SRM methods being less supported than CDR measures (Royal Society 2009; IPSOS Mori 2010). Similarly, Wright et al. (2014) find in a survey for Australia and New Zealand that respondents have more positive associations with CDR measures than with SRM. A direct comparison of the acceptance of the three measures has not yet been performed.

While there are a number of studies that investigate the effect of additional information (research question 2) on the acceptance of CCS, there are none for SRM and afforestation. The studies on CCS find conflicting results. On the one hand, several studies find a decrease in acceptance when respondents receive more information (Ha-Duong et al. 2009; Itaoka et al. 2009; L'Orange et al. 2011). Moreover, initially neutral respondents are significantly more likely to have a negative attitude toward CCS after receiving more information (Itaoka et al. 2012). On the other hand, several studies find an increase in acceptance when respondents receive more information (Curry 2004; Curry et al. 2005; Curry et al. 2007; De Best-Waldhober et al. 2009; Itaoka et al. 2004; Shackley et al. 2005; Tokushige et al. 2007a; Tokushige et al. 2007b). Pietzner et al. (2011) show that the effect of information differs across Europe. Altogether, these studies provide little systematic evidence on the role that personal characteristics might play for the conflicting results.

The influence of personal characteristics on acceptance (research question 3) has been analysed before. Studies have focused in particular on the following determinants: perceived seriousness of climate change, risk attitudes, values, and trust in institutions.

For SRM, surveys have been used to analyse the influence of several characteristics on acceptance (Mercer et al. 2011; Merk et al. 2015; Pidgeon et al. 2012; Spence et al. 2010; Sugiyama and Fujiwara 2012). These studies find that the perceived seriousness of climate change increases acceptance of SRM. In addition, Kahan et al. (2015) show that learning about CE increases the risk perception of climate change. Egoistic values generally increase the acceptance of CE measures like SRM, whereas altruism does not have a significant impact (Corner and Pidgeon 2014). An egalitarian worldview decreases the acceptance of CE (Bellamy and Hulme 2011).

In addition, the valuation of security and respondents' willingness to take risks might influence acceptance. For the latter, Merk et al. (2015) report a positive effect on acceptance of SRM. Ecological values about the relationship between humans and nature are an important factor for the acceptance of large-scale interventions like SRM. For example, the attitude that humans will eventually learn to control nature increases the acceptance of various kinds of SRM research and deployment, while a strong perception of the balance of nature being fragile decreases acceptance (Merk et al. 2015). In general, the risk perception literature also finds that perceived naturalness is an important determinant of risk perception (Slovic 2000). In the context of CE, respondents' perceived naturalness of different CE measures determines their perception (Corner et al. 2013; Corner and Pidgeon 2014; Macnaghten and Szerszynski 2013).

Beyond these general attitudes, also specific attitudes toward the technology influence the perception. The attitude that humans should not manipulate nature in the way SRM does, decreases the acceptance (Merk et al. 2015). Carr (2014) argues that also the perception of SRM as playing God might influence its acceptance, as religiousness determines the support for other technologies, e.g., nanotechnology.

Trust in institutions positively influences the acceptance of CCS as well as SRM (Terwel et al. 2009; Merk et al. 2015). Findings for other risky technologies suggest, however, that it might be less important the more knowledgeable people are about the technology (Siegrist 2000). This suggests that people rely on institutions when they know little but rely on themselves when they know more.

In addition, there are socio-demographic factors that potentially influence acceptance. Previous findings on the effect of education on acceptance are contradictory: Pidgeon et al. (2012) find a higher level of acceptance of SRM for highly educated people while Merk et al. (2015) find the reverse. Previous studies find that women tend to be more sceptical about CCS (Ha-Duong et al. 2009; Miller et al. 2007), while the results for CE measures are less clear (Pidgeon et al. 2012; Corner and Pidgeon 2014; Merk et al. 2015). The gender difference might be caused by the framing and the amount of information. L'Orange et al. (2011) find lower levels of acceptance for women than for men in a basic information setting. Additional information on the monitoring of CCS has only a downward impact on men's level of acceptance, which is then similar to the impact on women.

Altogether, our study contributes to the existing literature in various ways. First, we provide insights into the perception of a heterogeneous set of new measures in Germany and compare them using a consistent framework for all three measures. Second, we are able to directly compare the levels of acceptance and their determinants across measures. Our selection of determinants is based on previous findings from the literature. In addition, we aim at providing new insights into the so far contradictory effect of education on acceptance. Education can be interpreted as a proxy of whether decisions are made intuitively or not. To address this more directly, we include the cognitive reflection test (CRT)

proposed by Frederick (2005). It distinguishes intuitive from reflective decision makers and correlates with decision making. People who make more intuitive decisions are more risk-averse and more impatient than more reflective people (Frederick 2005, Oechssler et al. 2009). Additionally, more intuitive people are more susceptible to behavioural biases (Oechssler et al. 2009; Bergman et al. 2010; Hoppe and Kusterer 2011), which could be relevant in the context of processing information. Third, we analyse the effect of information on the acceptance of the three measures. Hence, we can address potential differences in the direction and the magnitude of the effect of information between the measures. Fourth, we are the first to broadly analyse the interaction of information with personal predispositions, values and attitudes. While the influence of personal characteristics on acceptance (research question 3) has been analysed before, the interaction of the treatment effect of additional information with personal characteristics (research question 4) has not yet been researched. This approach may provide insights into the reasons for the hitherto inconclusive results on the effect of information, which could be caused by differences in the survey design or the national context of previous studies.

3. Data and survey design

Our study uses novel data from an online survey that we conducted in August/September 2013. Respondents were randomly assigned to one of the three measures SRM, afforestation, or CCS. For each measure, we implemented two treatments using a between-subjects design. The two treatments differed only with respect to the amount of information that respondents received about the measure. Respondents aged 18 or above were recruited via an online panel. They were sampled using quotas for the characteristics of gender, age, and state of residence. In total, our working sample includes 3526 observations.¹⁴ The average age was 47 years. Half of our respondents were male. Thirty-six per cent of our respondents have a higher education entrance certificate. The average number of observations per treatment group is 588, ranging from 577 to 608.

The survey consisted of the following four parts. Table A-1 in the appendix reports all survey items used in our analysis and the scales on which they are measured.

In the first part, we elicited respondents' risk attitude using the scale implemented by Dohmen et al. (2011). Next, we elicited respondents' perception of the seriousness of climate change and their ecological values. The ecological values were measured by five items from the New Ecological Paradigm Scale (NEP, Dunlap et al. 2000). Before we provided respondents in the next part of the survey with information on one of the measures, we asked them about their awareness of the respective measure.

¹⁴ A total of 3909 respondents completed the survey. We dropped observations from respondents whom we identified as either speeders or straight-liners. Speeders are respondents who completed the survey in less than 9 minutes. Straight-liners are respondents who ticked the same answer within at least two blocks of questions.

The second part contained the information treatment. Our aim was to present the information in a clear yet scientifically correct way. Unlike previous studies, we provided information using animated graphics videos. The animations explained the information graphically and were supported by verbal explanations spoken by a professional radio presenter.¹⁵ The videos were embedded into the survey. Respondents who were not able to listen to or to play the video were excluded at the beginning of the survey. It was not possible to skip or fast-forward the video. The video first provided respondents with information on anthropogenic climate change and its likely consequences. The video then introduced mitigation, adaptation and either SRM, afforestation or CCS as three possibilities to address climate change. Afterwards, the video explained the respective measure in more detail. The video contained either basic information (BI treatment) or full information (FI treatment) on the respective measure. In the BI treatment, respondents received background information, i.e., the measure's underlying mechanisms and its impact on climate change. In the FI treatment, respondents watched the BI information video, but in addition, the video informed them about the current state of research and the potential benefits and risks of the specific measure. The information was based on peer-reviewed papers and scientific reports (taken from, e.g., Crutzen 2006, IPCC 2007; IPCC 2012; OrNSTEIN et al. 2009; Royal Society 2009; UBA 2008). External experts checked the information for correctness and clarity. After watching the video, we asked respondents about the clarity of the video. More than 98% of the respondents across all treatments indicated that they understood the video well or very well.

In the third part, we elicited respondents' acceptance of the respective measure. Next, we elicited respondents' attitude toward a measure such as 'humans should not interfere with nature in this way' or '[...] is the easy way out'. We also measured trust in various actors or institutions to act in the interest of society and the environment. Thereafter, we elicited respondents' egoistic, altruistic and security values. These values were measured using items from the Schwartz Personal Value Questionnaire (PVQ5X, Schwartz et al. 2012, Beyerlein personal communication). Next, respondents completed the cognitive reflection test (Frederik 2005). The cognitive reflection test (CRT) indicates whether a respondent is a rather intuitive (low CRT score) or a rather reflective person (high CRT score).

The fourth part contained questions on the socio-demographic characteristics of respondents. In particular, we elicited information on the respondents' gender, age, state of residence and education. A respondent with a higher education entrance certificate is coded as having a high level of education in our analysis. In addition, we elicited the respondents' religiousness.

Respondents could refrain from answering. The option 'don't know' was included in every question.

¹⁵ An English translation of the German script of the video is provided in appendix.

4. Methodology

Our analysis consists of two steps. In the first step, we use a descriptive analysis to compare the respondents' perception of the different measures (research question 1) and make a first assessment of the differences in the effect of information on acceptance. In the second step, we use a regression framework to analyse the determinants of acceptance for the three different measures as well as the size of the treatment effect. We further investigate whether respondents react differently to information depending on their personal characteristics. To address research questions (2) and (3a) on the determinants of acceptance and the role of information, we estimated, separately for each measure, the following equation:

$$(I) \quad acceptance_i = \alpha + \beta info_i + \gamma X_i + \varepsilon_i.$$

To address research question (3b) on the interaction of information and personal characteristics, we estimated the following type of equation:

$$(II) \quad acceptance_i = \alpha + \beta info_i + \gamma X_i + \delta(x_i \times info_i) + \varepsilon_i.$$

The dependent variable *acceptance* measures respondent *i*'s level of acceptance of a specific measure. It takes ordered values from 0 ('strongly disagree') to 3 ('strongly agree'). The dummy variable *info* takes a value of 0 if the respondent participated in the BI treatment and 1 if she participated in the FI treatment. *X* is a vector of personal characteristics (risk attitude, perceived seriousness of climate change, values, attitudes, trust, cognitive reflection, awareness, and socio-economic characteristics). The responses for ecological values (NEP), egoistic values, altruistic values, security values, and trust are standardised indices. The characteristic awareness controls for the influence of information from sources other than ours. It is included as a dummy variable, which takes a value of 0 if a respondent had never heard about a measure before and 1 if the respondent had heard at least a little bit about the measure before. The coefficient of the interaction term δ shows how the information effect changes with a one-unit change in the personal characteristic.

Summary statistics can be found in table A-2 in the appendix.

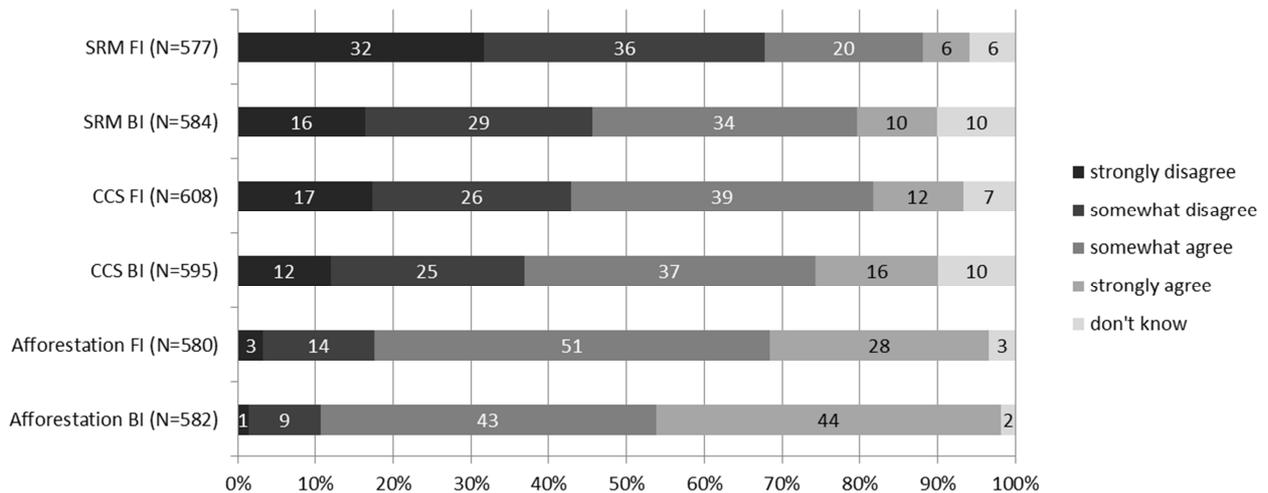
5. Results

5.1 Descriptive statistics

Self-reported awareness differs significantly and strongly between SRM, CCS and afforestation (Wilcoxon rank sum tests $p \leq 0.001$). SRM is not well known: Less than a quarter of respondents have heard at least a little bit about it (22%). In contrast, a majority of respondents have heard at least a little bit about CCS (52%). For afforestation, we find an even higher awareness than for CCS. 60% of respondents state that they have heard at least a little bit about afforestation before.

Figure 1 shows respondents' acceptance of SRM, CCS and afforestation in the BI treatment and FI treatment. In general, we find that the share of respondents who strongly or somewhat agree with the use of a measure is highest for afforestation, followed by CCS and SRM. This ranking holds irrespective of the amount of information respondents received.¹⁶

Figure 1: Acceptance of SRM, CCS and afforestation in the FI and BI treatments



Note: The survey asked the following question: “We should use [...] to counteract climate change.” Own presentation.

Concerning the effect of information, our results show a clear picture. For each measure, we find that additional information (FI treatment) has a negative effect on acceptance (Wilcoxon rank sum tests, SRM $p < 0.001$, CCS $p = 0.007$, afforestation $p < 0.001$). The decrease in acceptance is weakest for CCS. 53% of the respondents who received only basic information on CCS agree that CCS should be used to counteract climate change. The share decreases only marginally to 51% in the FI treatment. The effect of information is strongest for SRM (44% versus 26%). For afforestation, the share of respondents who agree with using afforestation to counteract climate change is eight percentage points lower in the FI treatment than in the BI treatment (87% versus 79%).

5.2 Regression analysis

Table 1 provides, for each measure, the results of equation (I) on the determinants of acceptance and the role of information. Table 2 provides the results of equation (II) on the interaction effects. In columns (2) to (6) of table 2, we sequentially add interaction terms between info and one personal characteristic. While we ran regressions including interaction terms with all personal characteristics, table 2 only reports coefficient estimates for interaction terms that are statistically significant for at

¹⁶ In the following, we use the term ‘agree’ when respondents choose ‘strongly agree’ or ‘somewhat agree’ and the term ‘disagree’ when respondents choose ‘strongly disagree’ or ‘somewhat disagree’.

least one measure. Tables A-3 to A-5 in the appendix report the complete regression results. All results are based on OLS regressions.¹⁷

Determinants of acceptance

Our results presented in table 1 reveal that, for each of the three measures, the treatment variable info has a significantly negative effect on acceptance. This finding confirms our descriptive finding that acceptance is generally lower in the FI treatment than in the BI treatment. We find the strongest effect for SRM. The acceptance of SRM decreases by 0.29 points between the BI and FI treatments. The acceptance of CCS is 0.17 points lower in the FI treatment than in the BI treatment. The results are similar for afforestation: the acceptance decreases by 0.18 points between the BI and FI treatments. Thus, we find for all three measures systematic evidence that information generally reduces acceptance.

Our regression results also show that, for SRM, awareness is a significant determinant of acceptance. For SRM, respondents who were aware of SRM before the survey show a lower acceptance. For CCS and afforestation, we do not find any significant effect of awareness on acceptance. Moreover, we find that respondents' risk attitude has a significant effect on the acceptance of SRM and CCS: Risk-seeking respondents are more likely to accept the use of a measure than risk-averse respondents. The perception of the seriousness of climate change also determines acceptance. Respondents who perceive climate change as a more serious problem also have a higher acceptance of any measure.

Values are also important determinants of acceptance. For SRM, we find that more egoistic respondents tend to accept the measure more readily than less egoistic respondents. For CCS, security loving respondents show a statistically significant higher acceptance than less security loving respondents. For afforestation, respondents with higher scores on ecological values and more egoistic respondents have a significantly higher acceptance. We also find that attitudes significantly affect the acceptance of all three measures. Respondents who either think that a given measure is the easy way out or that humans should not manipulate nature this way have a significantly lower acceptance. Trust in institutions has a significant positive effect. Cognitive reflection has a significant negative effect on acceptance of all three measures.

Finally, we also find that socio-demographic variables influence acceptance. For both SRM and afforestation, more religious respondents reveal a significantly higher acceptance. For SRM, women show a higher acceptance than men. In contrast, we do not find significant gender differences for the acceptance of CCS and afforestation. We also analysed whether the level of acceptance varies between the different states in Germany. We find that the acceptance of CCS in Schleswig-Holstein and Lower

¹⁷ As a robustness check, we also performed ordered logit regressions. The results are very similar to the OLS results.

Saxony is 0.21 points lower than in the rest of Germany. These are regions that faced public protest against onshore CCS in the past. For SRM and afforestation, we do not find significant regional differences in the level of acceptance.

Table 1: OLS regression results equation (I)

Acceptance	SRM	CCS	Afforestation
info	-0.29 ^{***} (0.05)	-0.17 ^{***} (0.05)	-0.18 ^{***} (0.04)
awareness	-0.12 ^{**} (0.06)	-0.02 (0.05)	0.04 (0.04)
risk attitude	0.05 ^{***} (0.01)	0.03 ^{**} (0.01)	0.02 (0.01)
seriousness of climate change	0.13 ^{***} (0.04)	0.14 ^{***} (0.04)	0.13 ^{***} (0.04)
<i>Values</i>			
ecological	-0.00 (0.05)	-0.09 [*] (0.05)	0.11 ^{**} (0.04)
altruistic	-0.03 (0.04)	0.01 (0.04)	-0.02 (0.03)
egoistic	0.11 ^{***} (0.04)	0.04 (0.04)	0.09 ^{***} (0.03)
security	0.06 (0.04)	0.11 ^{***} (0.04)	0.07 ^{**} (0.03)
<i>Attitudes</i>			
is easy way out	-0.14 ^{***} (0.04)	-0.14 ^{***} (0.04)	-0.11 ^{***} (0.03)
not manipulate this way	-0.43 ^{***} (0.04)	-0.39 ^{***} (0.04)	-0.26 ^{***} (0.03)
<i>Other Factors</i>			
trust	0.31 ^{***} (0.04)	0.32 ^{***} (0.04)	0.24 ^{***} (0.04)
cognitive reflection	-0.09 ^{***} (0.02)	-0.09 ^{***} (0.02)	-0.04 [*] (0.02)
<i>Socio-demographics</i>			
religiousness	0.07 ^{***} (0.02)	0.00 (0.02)	0.05 ^{**} (0.02)
female	0.11 ^{**} (0.05)	0.08 (0.05)	-0.03 (0.05)
high education	-0.13 ^{**} (0.05)	-0.10 [*] (0.05)	-0.06 (0.05)
age	0.00 (0.00)	0.00 (0.00)	0.00 [*] (0.00)
region	-0.04 (0.06)	-0.21 ^{***} (0.07)	-0.03 (0.06)
constant	2.02 ^{***} (0.18)	2.22 ^{***} (0.18)	2.23 ^{***} (0.16)
Observations	846	897	898
Adjusted R^2	0.4775	0.4412	0.3202

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 0 (strongly disagree) to 3 (strongly agree).

Interaction terms

We find evidence that individuals' reactions to information depend to a certain extent on their personal characteristics (table 2).

For SRM and afforestation, we find that the negative effect of information on acceptance is larger for *women* than for *men*; women react much more strongly to information than men do. For SRM, informing respondents about SRM decreases acceptance by 0.20 points (SRM-2: *info*), for women acceptance decreases more than for men (0.41 points in the FI treatment; sum of *info* and *female * info*). Thus, the decline in acceptance is 0.21 points higher for women than for men, and this difference is statistically significant at the 5% level. Table 2 also provides evidence that this gender difference in acceptance vanishes in the FI treatment; between the two treatments, the acceptance of women declines by 0.21 points more than that of men. For afforestation, the acceptance of men does not differ statistically significantly between the FI treatment and the BI treatment (Aff-2: *info*). The acceptance of women, in contrast, is significantly lower in the FI treatment than in the BI treatment (sum of *info* and *female * info*). Hence, for afforestation, the negative overall effect of information is mostly explained by the negative effect on women.

For SRM, we also find that the effect of information depends on respondents' *risk attitude* (SRM-3: *risk attitude * info*). Respondents who are risk-seeking react less negatively to information than do risk-averse respondents. More specifically, the effect of information increases by 0.05 points for every one-unit increase in the risk-seeking factor. A plausible explanation for the positive sign of the interaction term is that risk-averse respondents put a higher weight on the risks of SRM when being informed about its risks and benefits. We also find for SRM that the perceived *seriousness of climate change* determines the effect of information (SRM-4). Respondents who perceive climate change as a serious problem have a higher acceptance of SRM (*seriousness of climate change*), but they react more negatively to information than respondents who do not perceive climate change as a serious problem. A one-point increase in the perceived seriousness of climate change decreases the effect of information by 0.14 points (SRM-4: *seriousness of climate change * info*). A likely explanation is that respondents who consider climate change to be a serious problem are more likely to consider the use of SRM in the first place (SRM-4: *seriousness of climate change*). Only for these respondents is additional information relevant to their acceptance. Conversely, respondents who do not perceive climate change as serious are not likely to consider the use of SRM, irrespective of the amount of information they receive.

We also find, that the negative effect of information on the acceptance of SRM is less pronounced for more *egoistic* respondents (SRM-6). They might perceive the additional information on the benefits more strongly and/or the additional information on the risks and side effects less strongly than less egoistic respondents. They might, therefore, show a less negative reaction to the additional

information. Finally, we find for CCS that more altruistic respondents react more negatively to information than less altruistic respondents (CCS-5).

Interaction terms between *info* and all other personal characteristics are not statistically significant determinants of the acceptance of any of the three measures. Interestingly, neither education nor cognitive reflection matter for the effect of additional information on acceptance. This finding suggests that the information provided is not understood differently depending on cognitive capacities.

Table 2: OLS regression results equation (II)

Acceptance	SRM					CCS					Afforestation				
	(SRM-2)	(SRM-3)	(SRM-4)	(SRM-5)	(SRM-6)	(CCS-2)	(CCS-3)	(CCS-4)	(CCS-5)	(CCS-6)	(Aff-2)	(Aff-3)	(Aff-4)	(Aff-5)	(Aff-6)
info	-0.20*** (0.06)	-0.55*** (0.12)	0.20 (0.24)	-0.29*** (0.05)	-0.30*** (0.05)	-0.13** (0.07)	-0.08 (0.14)	0.14 (0.27)	-0.16*** (0.05)	-0.17*** (0.05)	-0.07 (0.06)	-0.23** (0.11)	0.20 (0.27)	-0.18*** (0.04)	-0.18*** (0.04)
female	0.22*** (0.07)	0.11** (0.05)	0.10** (0.05)	0.11** (0.05)	0.11** (0.05)	0.12 (0.07)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)	0.09 (0.06)	-0.03 (0.05)	-0.03 (0.05)	-0.03 (0.05)	-0.03 (0.05)
risk attitude	0.05*** (0.01)	0.02 (0.01)	0.05*** (0.01)	0.05*** (0.01)	0.05*** (0.01)	0.03** (0.01)	0.04* (0.02)	0.03** (0.01)	0.03** (0.01)	0.03** (0.01)	0.01 (0.01)	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)	0.01 (0.01)
seriousness of climate change	0.13*** (0.04)	0.13*** (0.04)	0.21*** (0.05)	0.13*** (0.04)	0.13*** (0.04)	0.14*** (0.04)	0.14*** (0.04)	0.18*** (0.06)	0.14*** (0.04)	0.14*** (0.04)	0.13*** (0.04)	0.13*** (0.04)	0.18*** (0.05)	0.13*** (0.04)	0.13*** (0.04)
altruistic	-0.04 (0.04)	-0.03 (0.04)	-0.04 (0.04)	-0.03 (0.05)	-0.03 (0.04)	0.01 (0.04)	0.01 (0.04)	0.01 (0.04)	0.07 (0.05)	0.01 (0.04)	-0.02 (0.03)	-0.02 (0.03)	-0.02 (0.03)	0.01 (0.04)	-0.02 (0.03)
egoistic	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.04 (0.05)	0.05 (0.04)	0.04 (0.04)	0.04 (0.04)	0.05 (0.04)	0.05 (0.06)	0.09*** (0.03)	0.09*** (0.03)	0.09*** (0.03)	0.09*** (0.03)	0.07* (0.04)
female * info	-0.21** (0.09)					-0.08 (0.09)					-0.25*** (0.08)				
risk attitude * info		0.05** (0.02)					-0.02 (0.02)					0.01 (0.02)			
seriousness of climate change * info			-0.14** (0.07)					-0.09 (0.07)					-0.11 (0.07)		
altruistic * info				0.00 (0.07)					-0.11* (0.07)					-0.06 (0.06)	
egoistic * info					0.13** (0.07)					-0.01 (0.07)					0.04 (0.06)
Other controls	All	All	All	All	All	All	All	All	All	All	All	All	All	All	All
Observations	846	846	846	846	846	897	897	897	897	897	898	898	898	898	898
Adjusted R ²	0.4801	0.4802	0.4801	0.4769	0.4798	0.4410	0.4409	0.4417	0.4427	0.4406	0.3260	0.3196	0.3221	0.3202	0.3199

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Note: Acceptance is measured on a scale of 0 (strongly disagree) to 3 (strongly agree). Other controls include: awareness, ecological values, security values, attitudes, trust, cognitive reflection, religiousness, high education, age, and region.

6. Discussion and conclusion

This paper provides novel survey evidence for Germany on the perception of SRM, CCS and afforestation. These measures are currently controversially debated options to address climate change. Unlike previous surveys, we use a consistent research design for all measures and can thus directly compare the perceptions of the three measures. By examining the effect of information on perception, our paper also provides a possible projection on how acceptance might evolve in the future—as more and more information on CE and CCS becomes available. Finally, we also provide initial insights into how the effect of information differs across different subgroups of society.

Based on a consistent framework we are able to substantiate previous findings by allowing for a direct comparison of results across the three measures. We find that current levels of awareness differ strongly between SRM, CCS and afforestation. SRM is rather unknown to the public. In contrast, CCS and afforestation are known to slightly more than half of the respondents. Further, we find strong differences in the acceptance between the measures. Acceptance is generally highest for afforestation, followed by CCS and SRM (e.g., Mercer et al. 2011; Curry et al. 2005). Regarding the potential determinants of acceptance; for most determinants, we find consistent results across all measures confirming previous findings; the perception that climate change is serious increases acceptance (e.g., Mercer et al 2011). Also attitudes, e.g., that ‘humans should not manipulate nature’, significantly decrease acceptance (e.g., Mercer et al. 2011). We also find that trust has a positive effect on acceptance (e.g., Terwel et al. 2009). Focusing on the so far inconclusive effect of education on acceptance, our results suggest that education has a sizeable negative effect on acceptance confirming findings of Merk et al. (2015) for SRM in Germany.

We included, novel to the literature, results of respondents’ CRT to address the issue further. We find that cognitive reflection significantly decreases acceptance of all three measures, even when controlling for education and risk attitudes. More reflective decision makers are more sceptical about the measures.

Additional information significantly decreases the acceptance of all three measures—without changing their relative rankings. The difference in acceptance between the three measures is substantial before receiving full information and remains substantial after receiving full information. In particular, for SRM, we find a strong effect of information. While previous findings on the effect of additional information for CCS were mixed (e.g., Ha-Duong et al. 2009; De Best-Waldhober et al. 2009), we find a consistent negative effect of information on acceptance for the three measures analysed. Differences in the information presented, the wording of the questions, and the questionnaire design as well as the country where the survey was conducted might explained the mixed findings.

As pointed out above, results of previous findings disagree on the effect of gender on acceptance. Unlike, Ha-Duong et al. (2009) and Miller et al. (2007) we find no effect of gender on the acceptance of CCS. Also, we are unable to confirm findings of L'Orange et al. (2011) that differences depend on the amount of information provided. However, results are, again, not readily comparable; previous studies' results depend on the results of summary statistics while we obtained results from multiple regression analysis. Like Pidgeon et al. (2012) we find evidence that women show a higher acceptance of SRM. We also find that they respond particularly strongly to information. Women have higher acceptance than men after having received basic information. However, this gender difference in acceptance vanishes after having received full information, as women react much more negatively to information than men. In addition, we find evidence that other personal characteristics such as risk attitude or values determine how information affects acceptance. This finding suggests that information affects subgroups of society very differently. While information lowers acceptance for some of them (i.e. less egoistic, more risk averse, those who perceive climate change as a serious problem) others are less affected by information. Communication strategies would have to take this into account. We find the strongest indication of individual-specific differences in the effect of information for SRM. Presumably, this is because the effect of information is greatest for this measure.

Overall, our results provide insights into the current perception of three hotly debated measures to address climate change. They also help to project how public opinions might evolve in the future when more information on the risks and benefits of these measures becomes available. Thus, our paper contributes to the dialog between policymakers, scientists and the general public on suitable ways to address climate change. The variability in acceptance found in our data also suggests that communication with the public should be an on-going process and that public opinions must be taken into account to ensure the legitimacy of research (Carr et al. 2013).

As other survey results, our findings must be interpreted cautiously. Corner et al. (2012) note that respondents' lack of prior knowledge of the topic creates the risk that "participants have been told what they are responding to rather than deciding for themselves how to interpret the item." We, therefore, paid specific attention to ask balanced questions without leading cues. In addition, the 'don't know' option was included in every item to signal that not answering was acceptable. The sequence of items within the questions was randomized, and we arranged the questions in a way that prevents or minimizes bias due to order effects. We also consulted with experts on survey design to ensure that our questionnaire met current quality standards.

Given the novelty of the measures analysed, the information of our respondents is mostly drawn from the video shown in the survey. While we made sure that the information in the video is

regarded as complete and balanced by scientists, it must be noted, however, that the way in which information is framed might influence responses (Corner and Pidgeon 2014). Our study thus can only provide a snapshot of public acceptance obtained in a highly controlled setting at a time when strong media coverage and lively public discourse are still absent. Hence, it provides an indication for current and future acceptance based on the assumption that respondents regard the provided information as neutral. Yet, the future discourse on CE and CCS might be strongly influenced by information from the media, from NGOs or from the industry. Such information might be unbalanced and shape perceptions differently. Moreover, the effect of information on acceptance might vary over time.

Despite these limitations, which provide natural reference points for future research, our survey makes a valuable contribution to the emerging public debate on new measures to address climate change. In particular, our results suggest that only providing information, without actively involving the public, might further reduce the acceptance of CE and CCS projects --and might thus put such projects to a premature hold. Therefore, a broad public discourse, allowing for active engagement, is needed if CE and CCS should become publically accepted --and thus politically viable--options to counteract climate change (see also Corner et al. 2012).

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8. Appendix

Table A-1: Survey items

<i>Question and items</i>	<i>response scale</i>
Risk attitude	
Are you generally a person who is fully prepared to take risks or do you try to avoid taking risks?	risk averse (0) - risk seeking (10)
Seriousness of climate change	
Global warming is a serious problem.	strongly disagree (0) - strongly agree (3)
Ecological values (Cronbach's $\alpha = 0.5756$)	
The Earth is like a spaceship with very limited room and resources.	strongly disagree (0) - strongly agree (3)
Humans were meant to rule over the rest of nature.	
The balance of nature is very delicate and easily upset.	
Humans will eventually learn enough about how nature works to be able to control it.	
If things continue on their present course, we will soon experience a major ecological catastrophe.	
Altruistic values (Cronbach's $\alpha = 0.7224$)	
She thinks it is important that every person has equal opportunities in life.	very dissimilar (0) - very similar (3)
She works to promote peace among diverse groups	
Protecting society's weak and vulnerable members is important to her.	
Caring for the well-being of people she is close to is important to her.	
Egoistic values (Cronbach's $\alpha = 0.7724$)	
She wants people to do what she says.	very dissimilar (0) - very similar (3)
Being wealthy is important to her.	
It is important to her to be the one who tells the others what to do.	
It is important to her to be the most influential person in any group.	
Security values (Cronbach's $\alpha = 0.7114$)	
Her personal security is extremely important to her.	very dissimilar (0) - very similar (3)
She avoids anything that might endanger his safety.	
It is important to her to live in secure surroundings.	
Having order and stability in society is important to her.	
Awareness	
Have you ever heard about [...] before or have you never heard about it before?	No, I have never heard about it Yes, I have heard a little about it. Yes, I have heard a lot about it
Acceptance	
We should use [...] to counteract climate change.	strongly disagree (0) - strongly agree (3)
Attitudes	
[...] is the easy way out.	strongly disagree (0) - strongly agree (3)
Humans should not be manipulating nature in this way.	

Questions and items (continued)	response scale
<p>Trust (Cronbach's $\alpha = 0.7942$)</p> <p>How strongly do you trust that these groups will act in the interest of society and the environment?</p> <ul style="list-style-type: none"> Federal government Companies involved in [...] projects Environmental organisations Media Researchers studying at publicly funded research institutes United Nations European Union 	<p>strongly disagree (0) - strongly agree (3)</p>
<p>Cognitive reflection</p> <p>A bat and a ball cost \$1.10 in total. The bat costs \$1.00 more than the ball. How much does the ball cost?</p> <p>If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?</p> <p>In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake?</p>	<p>any number</p>
<p>Religiousness</p> <p>How religious are you?</p>	<p>not religious at all (0) - very religious (3)</p>
<p>Education</p> <p>What is your highest degree?</p>	<p>7 degrees</p>
<p>Region</p> <p>In which Federal State do you live?</p>	<p>16 states</p>

Table A-2: Summary statistics

<i>Variables</i>	<i>Domain</i>	<i>SRM</i>		<i>CCS</i>		<i>Afforestation</i>	
		<i>mean</i>	<i>standard deviation</i>	<i>mean</i>	<i>standard deviation</i>	<i>mean</i>	<i>standard deviation</i>
acceptance	0 - 3	1.21	0.93	1.56	0.93	1.20	0.74
awareness	0 (have never heard); 1 (have heard at least a little bit)	0.22		0.52		0.60	
risk attitude	0 - 10	5.39	2.26	5.36	2.20	5.37	2.31
seriousness of climate change	0 - 3	2.51	0.71	2.51	0.71	2.51	0.70
ecological values	standardised index	-0.029	0.61	0.017	0.61	0.001	0.61
altruistic values	standardised index	-0.023	0.74	0.039	0.74	-0.026	0.74
egoistic values	standardised index	0.001	0.77	-0.024	0.74	0.032	0.80
security values	standardised index	-0.002	0.74	0.019	0.73	-0.025	0.73
attitudes_ easy way out	0 - 3	2.17	0.84	2.09	0.85	1.69	0.85
attitudes_not manipulate in this way	0 - 3	2.19	0.85	2.02	0.88	1.21	0.85
trust	standardised index	-0.021	0.67	-0.059	0.67	0.095	0.66
cognitive reflection test	0 - 3	0.98	1.03	1.06	1.03	1.05	1.03
religiousness	0 - 3	1.01	0.94	1.04	0.97	1.02	0.96
female	0 (Male); 1 (Female)	49%		50%		49%	
high education	0 (other); 1 (A level)	36%		35%		36%	
age	18 - 87	47	15.33	48	15.33	47	15.15
region	0 (other); 1 (Schleswig-Holstein or Lower Saxony)	14%		12%		13%	
N		1161		1203		1162	

Table A-3: OLS regression results for SRM

Acceptance of SRM	(SRM-1)	(SRM-2)	(SRM-3)	(SRM-4)	(SRM-5)	(SRM-6)
info	-0.29*** (0.05)	-0.20*** (0.06)	-0.55*** (0.12)	0.20 (0.24)	-0.29*** (0.05)	-0.30*** (0.05)
awareness	-0.12** (0.06)	-0.11** (0.06)	-0.12** (0.06)	-0.12** (0.06)	-0.12** (0.06)	-0.11** (0.06)
risk attitude	0.05*** (0.01)	0.05*** (0.01)	0.02 (0.01)	0.05*** (0.01)	0.05*** (0.01)	0.05*** (0.01)
seriousness of climate change	0.13*** (0.04)	0.13*** (0.04)	0.13*** (0.04)	0.21*** (0.05)	0.13*** (0.04)	0.13*** (0.04)
<i>Values</i>						
ecological	-0.00 (0.05)	-0.01 (0.05)	0.00 (0.05)	-0.01 (0.05)	-0.00 (0.05)	-0.00 (0.05)
altruistic	-0.03 (0.04)	-0.04 (0.04)	-0.03 (0.04)	-0.04 (0.04)	-0.03 (0.05)	-0.03 (0.04)
egoistic	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.04 (0.05)
security	0.06 (0.04)	0.06 (0.04)	0.06 (0.04)	0.06 (0.04)	0.06 (0.04)	0.06 (0.04)
<i>Attitudes</i>						
is easy way out	-0.14*** (0.04)	-0.14*** (0.04)	-0.14*** (0.04)	-0.14*** (0.04)	-0.15*** (0.04)	-0.14*** (0.04)
not manipulate this way	-0.43*** (0.04)	-0.43*** (0.04)	-0.43*** (0.04)	-0.42*** (0.04)	-0.43*** (0.04)	-0.43*** (0.04)
<i>Other Factors</i>						
trust	0.31*** (0.04)	0.31*** (0.04)	0.31*** (0.04)	0.31*** (0.04)	0.31*** (0.04)	0.31*** (0.04)
cognitive reflection	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)
<i>Socio-demographics</i>						
religiousness	0.07*** (0.02)	0.07*** (0.02)	0.07*** (0.02)	0.07*** (0.02)	0.07*** (0.02)	0.07*** (0.02)
female	0.11** (0.05)	0.22*** (0.07)	0.11** (0.05)	0.10** (0.05)	0.11** (0.05)	0.11** (0.05)
high education	-0.13** (0.05)	-0.13** (0.05)	-0.14*** (0.05)	-0.13** (0.05)	-0.13** (0.05)	-0.14*** (0.05)
age	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
region	-0.04 (0.06)	-0.05 (0.06)	-0.05 (0.06)	-0.04 (0.06)	-0.04 (0.06)	-0.04 (0.06)
<i>Interaction Terms</i>						
female * info		-0.21** (0.09)				
risk attitude * info			0.05** (0.02)			
seriousness of climate change * info				-0.14** (0.07)		
altruistic * info					0.00 (0.07)	
egoistic* info						0.13** (0.07)
constant	2.02*** (0.18)	1.95*** (0.18)	2.15*** (0.19)	1.82*** (0.21)	2.02*** (0.18)	2.00*** (0.18)
Observations	846	846	846	846	846	846
Adjusted R ²	0.4775	0.4801	0.4802	0.4801	0.4769	0.4798

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A-3: OLS regression of SRM acceptance. Note: Acceptance is measured on a scale of 0 (strongly disagree) to 3 (strongly agree). All other variables are also measured on scales of 0 to 3. Exceptions are dummy variables (info, awareness, female, high education, region), risk attitude (scale is from 0 to 10), and age. Variables for values and trust are standardised indices.

Table A-4: OLS regression results for CCS

Acceptance of CCS	(CCS-1)	(CCS-2)	(CCS-3)	(CCS-4)	(CCS-5)	(CCS-6)
info	-0.17*** (0.05)	-0.13** (0.07)	-0.08 (0.14)	0.14 (0.27)	-0.16*** (0.05)	-0.17*** (0.05)
awareness	-0.02 (0.05)	-0.02 (0.05)	-0.02 (0.05)	-0.02 (0.05)	-0.02 (0.05)	-0.02 (0.05)
risk attitude	0.03** (0.01)	0.03** (0.01)	0.04* (0.02)	0.03** (0.01)	0.03** (0.01)	0.03** (0.01)
seriousness of climate change	0.14*** (0.04)	0.14*** (0.04)	0.14*** (0.04)	0.18*** (0.06)	0.14*** (0.04)	0.14*** (0.04)
<i>Values</i>						
ecological	-0.09* (0.05)	-0.09* (0.05)	-0.09* (0.05)	-0.09** (0.05)	-0.10** (0.05)	-0.09* (0.05)
altruistic	0.01 (0.04)	0.01 (0.04)	0.01 (0.04)	0.01 (0.04)	0.07 (0.05)	0.01 (0.04)
egoistic	0.04 (0.04)	0.05 (0.04)	0.04 (0.04)	0.04 (0.04)	0.05 (0.04)	0.05 (0.06)
security	0.11*** (0.04)	0.11*** (0.04)	0.11*** (0.04)	0.10*** (0.04)	0.10*** (0.04)	0.11*** (0.04)
<i>Attitudes</i>						
is easy way out	-0.14*** (0.04)	-0.14*** (0.04)	-0.14*** (0.04)	-0.15*** (0.04)	-0.15*** (0.04)	-0.14*** (0.04)
not manipulate this way	-0.39*** (0.04)	-0.39*** (0.04)	-0.39*** (0.04)	-0.39*** (0.04)	-0.39*** (0.04)	-0.39*** (0.04)
<i>Other Factors</i>						
trust	0.32*** (0.04)	0.32*** (0.04)	0.33*** (0.04)	0.33*** (0.04)	0.32*** (0.04)	0.32*** (0.04)
cognitive reflection	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)	-0.09*** (0.02)
<i>Socio-demographics</i>						
religiousness	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)	0.00 (0.02)
female	0.08 (0.05)	0.12 (0.07)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)	0.08 (0.05)
high education	-0.10* (0.05)	-0.10* (0.05)	-0.10* (0.05)	-0.10* (0.05)	-0.10* (0.05)	-0.10* (0.05)
age	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
region	-0.21*** (0.07)	-0.21*** (0.07)	-0.21*** (0.07)	-0.21*** (0.07)	-0.21*** (0.07)	-0.21*** (0.07)
<i>Interaction Terms</i>						
female * info		-0.08 (0.09)				
risk attitude * info			-0.02 (0.02)			
seriousness of climate change * info				-0.09 (0.07)		
altruistic * info					-0.11* (0.07)	
egoistic* info						-0.01 (0.07)
Constant	2.22*** (0.18)	2.20*** (0.18)	2.18*** (0.19)	2.09*** (0.22)	2.21*** (0.18)	2.22*** (0.18)
Observations	897	897	897	897	897	897
Adjusted R ²	0.4412	0.4410	0.4409	0.4417	0.4427	0.4406

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A-4: OLS regression of CCS acceptance. Note: Acceptance is measured on a scale of 0 (strongly disagree) to 3 (strongly agree). All other variables are also measured on scales of 0 to 3. Exceptions are dummy variables (info, awareness, female, high education, region), risk attitude (scale is from 0 to 10), and age. Variables for values and trust are standardised indices.

Table A-5: OLS regression results for afforestation

Acceptance of afforestation	(Aff-1)	(Aff-2)	(Aff-3)	(Aff-4)	(Aff-5)	(Aff-6)
info	-0.18*** (0.04)	-0.07 (0.06)	-0.23** (0.11)	0.20 (0.27)	-0.18*** (0.04)	-0.18*** (0.04)
awareness	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)	0.04 (0.04)
risk attitude	0.02 (0.01)	0.01 (0.01)	0.01 (0.01)	0.02 (0.01)	0.02 (0.01)	0.01 (0.01)
seriousness of climate change	0.13*** (0.04)	0.13*** (0.04)	0.13*** (0.04)	0.18*** (0.05)	0.13*** (0.04)	0.13*** (0.04)
<i>Values</i>						
ecological	0.11** (0.04)	0.11** (0.04)	0.11** (0.04)	0.11** (0.04)	0.11** (0.04)	0.11** (0.04)
altruistic	-0.02 (0.03)	-0.02 (0.03)	-0.02 (0.03)	-0.02 (0.03)	0.01 (0.04)	-0.02 (0.03)
egoistic	0.09*** (0.03)	0.09*** (0.03)	0.09*** (0.03)	0.09*** (0.03)	0.09*** (0.03)	0.07 (0.04)
security	0.07** (0.03)	0.06* (0.03)	0.07** (0.03)	0.07** (0.03)	0.07** (0.03)	0.07** (0.03)
<i>Attitudes</i>						
is easy way out	-0.11*** (0.03)	-0.11*** (0.03)	-0.11*** (0.03)	-0.11*** (0.03)	-0.11*** (0.03)	-0.11*** (0.03)
not manipulate this way	-0.26*** (0.03)	-0.25*** (0.03)	-0.25*** (0.03)	-0.26*** (0.03)	-0.25*** (0.03)	-0.25*** (0.03)
<i>Other Factors</i>						
trust	0.24*** (0.04)	0.24*** (0.04)	0.24*** (0.04)	0.24*** (0.04)	0.24*** (0.04)	0.24*** (0.04)
cognitive reflection	-0.04* (0.02)	-0.05** (0.02)	-0.04* (0.02)	-0.04* (0.02)	-0.04* (0.02)	-0.04* (0.02)
<i>Socio-demographics</i>						
religiousness	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)	0.05** (0.02)
female	-0.03 (0.05)	0.09 (0.06)	-0.03 (0.05)	-0.03 (0.05)	-0.03 (0.05)	-0.03 (0.05)
high education	-0.06 (0.05)	-0.05 (0.05)	-0.06 (0.05)	-0.06 (0.05)	-0.06 (0.05)	-0.06 (0.05)
age	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
region	-0.03 (0.06)	-0.03 (0.06)	-0.03 (0.06)	-0.04 (0.06)	-0.03 (0.06)	-0.04 (0.06)
<i>Interaction Terms</i>						
female * info		-0.25*** (0.08)				
risk attitude * info			0.01 (0.02)			
seriousness of climate change * info				-0.11 (0.07)		
altruistic * info					-0.06 (0.06)	
egoistic* info						0.04 (0.06)
constant	2.23*** (0.16)	2.17*** (0.17)	2.26*** (0.17)	2.11*** (0.19)	2.24*** (0.16)	2.23*** (0.16)
Observations	898	898	898	898	898	898
Adjusted R ²	0.3202	0.3260	0.3196	0.3221	0.3202	0.3199

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table A-5: OLS regression of afforestation acceptance. Note: Acceptance is measured on a scale of 0 (strongly disagree) to 3 (strongly agree). All other variables are also measured on scales of 0 to 3. Exceptions are dummy variables (info, awareness, female, high education, region), risk attitude (scale is from 0 to 10), and age. Variables for values and trust are standardised indices.

1) Information provided in the SRM video:

Information provided both in the basic and full information video:

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere such as CO₂ ensure that some warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals, and plants to live on.

Since the start of industrialisation around 1850, people have emitted a great amount of greenhouse gases by burning coal, oil, and gas. These gases trap more heat in the atmosphere and cause a gradual increase in the average global temperature.

Since 1900, the global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in the average global temperature should not exceed 2°C compared to pre-industrial levels. This is called the 2°C target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To reach the 2°C target, the current level of emissions would have to be cut by more than half until 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of heavy precipitation events in many regions. It is likely that in the future, more areas will be affected by longer droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the emitted CO₂ is absorbed by the ocean, causing ocean acidification.

There are different ways to deal with climate change:

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is to reduce the global temperature by deploying solar radiation management (SRM).

Via SRM, some sunlight is reflected before it can warm the Earth. This can be accomplished by, for example, spraying sulphate particles into the atmosphere at a high altitude.

A similar phenomenon can be observed in nature: When large volcanoes erupt, similar particles are distributed across wide areas of the Earth's atmosphere, cooling the Earth.

The particles remain in the higher regions of the atmosphere for approximately two years. To prevent the Earth from heating up again, the spraying would have to be continued until the cause of global warming is removed. Because CO₂ remains in the atmosphere for a very long time, SRM might have to be used for several centuries. However, using SRM will not stop ocean acidification.

Information provided additional in the full information video:

Currently, the risks, the benefits, and the feasibility of SRM are being researched.

The use of SRM entails benefits as well as risks. One of the benefits is that global warming could be slowed more quickly than by cutting greenhouse gas emissions. This would buy additional time to remove the cause of climate change, i.e., the high concentration of greenhouse gases in the atmosphere. Massive and irreversible changes in the climate could be stopped before too much damage is done. Furthermore, it would be possible to stop climate change even if certain countries do not want to reduce their greenhouse gas emissions. Deploying SRM would be less expensive than reducing the consumption of fossil fuels.

The risks include a change in the amount of precipitation in most regions. Arid regions in particular would have to cope with even less rain. If the deployment of SRM was suddenly stopped, the global temperature would rise abruptly. The speed of this rise in temperature would lead to severe problems for humans and the environment. Because possible side effects would be trans-boundary, the use of SRM could cause international conflicts. Once used, SRM could take away people's motivation to change their lifestyle, and greenhouse gas emissions would continue to increase. Furthermore, there would be the possibility of further unknown and unforeseeable risks arising.

2) Information provided in the CCS video

Information provided both in the basic and full information video:

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere such as CO₂ ensure that some warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals, and plants to live on.

Since the start of industrialisation around 1850, people have emitted a great amount of greenhouse gases by burning coal, oil, and gas. These gases trap more heat in the atmosphere and cause a gradual increase in the average global temperature.

Since 1900, the global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in the average global temperature should not exceed 2°C compared to pre-industrial levels. This is called the 2°C target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To reach the 2°C target, the current level of emissions would have to be cut by more than half until 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of heavy precipitation events in many regions. It is likely that in the future, more areas will be affected by longer droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the emitted CO₂ is absorbed by the ocean, causing ocean acidification.

There are different ways to deal with climate change:

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is carbon capture and storage sub-seabed (CCS).

The CCS technology captures CO₂ from the industrial combustion of fossil fuels. The CO₂ is compressed and stored in suitable geological formations under the seabed. It is not released into the atmosphere. This process additionally uses approximately 25% of the generated energy, which increases the overall demand for fossil fuels.

On a small scale, CO₂ has already been stored in the ground for approximately 30 years. CO₂ is injected for the recovery of oil and gas to make this process easier. The experiences indicate a high level of storage safety.

Former oil and gas fields as well as sub-seabed saline aquifers are considered to be safe and permanently suitable deposits.

Pipelines and ships carry the compressed CO₂ to the deposits.

There, it is pumped into tiny hollows of the sub-seabed deposit, where it has to be stored for several thousands of years. During this time it merges with the rock and it is rendered permanently harmless.

Information provided additional in the full information video:

Scientists think further applied research on CCS would be useful. The processes, benefits and risks are already well understood.

Some expected benefits and risks of CCS are now introduced to you.

Benefits of CCS are that global warming as well as acidification of the oceans would be slowed down. Furthermore, deploying CCS would be less expensive than an energy transition from fossil fuels to renewable energies.

The risks of CCS include the possible leakage of CO₂ from the well or from the deposits caused by increased pressure. This could lead to a local acidification, which would endanger the biodiversity of that area.

3) Information provided in the afforestation video

Information provided both in the basic and full information video:

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere such as CO₂ ensure that some warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals, and plants to live on.

Since the start of industrialisation around 1850, people have emitted a great amount of greenhouse gases by burning coal, oil, and gas. These gases trap more heat in the atmosphere and cause a gradual increase in the average global temperature.

Since 1900, the global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in the average global temperature should not exceed 2°C compared to pre-industrial levels. This is called the 2°C target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To reach the 2°C target, the current level of emissions would have to be cut by more than half until 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of heavy precipitation events in many regions. It is likely that in the future, more areas will be affected by longer droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the emitted CO₂ is absorbed by the ocean, causing ocean acidification.

There are different ways to deal with climate change:

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is large-scale afforestation.

Growing trees gradually absorb CO₂ from the atmosphere and store it in the wood. By logging mature trees and replacing them with new ones, CO₂ can be continuously absorbed from the atmosphere. To prevent the CO₂ from re-entering the atmosphere, the logged trees are, for example, used as building material or buried.

To slow down climate change through afforestation, very large areas would have to be covered with trees. Suitable areas are especially tropical areas, the Sahara Desert and the Australian Outback.

Information provided additional in the full information video:

Scientists agree that the local effects have already been sufficiently researched. Further research is needed on the long-term effects on natural cycles.

Some expected benefits and risks of large-scale afforestation are now being introduced to you.

Benefits of large-scale afforestation are that global warming as well as acidification of the ocean would be slowed down. In addition, the quality of soil and water would be improved.

The risks include the high water consumption for the afforestation, which could lead to regional water scarcity. For the afforestation, agricultural areas would also have to be used. The afforestation of these areas could lead to food scarcity and thus increase food prices.

Furthermore, large-scale afforestation would slow down climate change more slowly than the mitigation of greenhouse gas emissions.

Paper IV: Exploring public perception of environmental technology over time

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Abstract

Public opinion has a substantial impact on political actions. However, public opinion might be driven by temporary emotions. If these emotions cool off over time, public opinion might change as well. This paper analyses how emotions drive public opinion over time for the case of an environmental climate engineering technology, namely solar radiation management (SRM). SRM is a possible strategy to fight climate change by injection of sulphate aerosols into the stratosphere. Its potential implementation involves major risks and faces strong public opposition. Using panel survey data, we show that most respondents initially show strong negative emotions towards SRM and reject the technology. However, emotions cool off over time and acceptance increases. The increase in acceptance is larger, the longer the cooling-off period between two surveys is.

Note: A modified version of this paper: Braun C, Rehdanz K, Schmidt U, 2016. Exploring public perception of environmental technology over time. Kiel Working Paper, 2027, Kiel Institute for the World Economy.

1. Introduction

Public opinion and public protest substantially influence policy making (Burstein 2003). There are many recent examples of public protest in Europe and elsewhere, such as the movements against the Transatlantic Trade and Investment Partnership (TTIP), austerity measures, nuclear energy or gene food. In many cases, public protests result in policy changes. For example, more than half of European Union member states have recently decided to ban their farmers from growing gene modified crops. This decision was taken after several protest movements in these countries demanded such ban.

Public protests are often driven by (negative) emotions (Van Stekelenburg and Klandermans 2010). Feelings of deprivation, such as anger, are particularly important in sparking protest (Walker and Smith 2002). Yet, such emotions and feelings can be temporary and may cool off over time. Consequently, protests might ebb away over time and protest movements become less powerful as emotions cool down. If this is indeed the case, policy maker might reasonably wait for emotions to cool off and public opinions to stabilize before taking political actions.

In fact, there is some evidence from the field that cooling-off periods can change behaviour and limit potentially detrimental effects of negative emotions. A prominent historical example in this regard is the custom of the British and Prussian armies of allowing complaints only the day after an incidence, so that soldiers are forced to rethink their complaints for a night.¹⁸ In a similar vein, divorce petitions in South Korea can only be filed after a cooling-off period. This practice has led to a significant decrease in divorce rates (Lee 2013). Laboratory experiments have more directly tested for the role of emotions in changing behaviour. In particular, cooling-off periods changed the behaviour of respondents when playing ultimatum games (Grimm and Mengel 2011), and they also reduced respondents' self-reported negative emotions and led to a change in punishment behaviour (Wang et al. 2011). These examples show that cooling-off periods can change human behaviour and make decisions less dependent of temporary emotions. Therefore, public protest, if caused by emotional decision making in a hot state, might ebb away over time when rethought in a cold state.

The present paper analyses to which extent negative emotions with respect to a new technology cool off over time and how this affects public opposition against this technology. The technology we consider for this exercise is solar radiation management (SRM). Among scientists, SRM is a controversially debated climate engineering (CE) technique that addresses climate change by the injection of sulphate aerosols into the stratosphere. On the one hand, SRM is supposed to be very effective in counteracting global warming; on the other hand, it involves large risks and uncertainties (Royal Society 2009; Klepper and Rickels 2014). Because the technology involves a deliberate manipulation of the earth's environmental system, information on public perception is one important prerequisite for making

¹⁸ Even today, this custom holds for the Military Complaints Regulations of the German Armed Forces.

informed decisions on research and deployment (e.g., Merk et al. 2015). So far, SRM is rather unknown to the broader public (Merk et al. 2015; Mercer et al. 2011) and media coverage is still low. This makes it a particularly interesting case to test for the influence of emotions on public perception over time.

Public opinion polls show that the majority of respondents oppose SRM after being informed about it (Bellamy and Hulme 2011; Borick and Rabe 2012; Kniebes et al. 2014; Mcnaghten and Szerszynski 2013). Public concern has also been voiced in protests against research projects on stratospheric aerosol injection and ocean iron fertilization (Stilgoe et al. 2013; Schäfer et al. 2015). Based on the empirical evidence available, one could conclude that public opposition against SRM is probably too strong for considering it to be an acceptable part of a climate policy portfolio. However, in the surveys conducted so far, respondents had to state their acceptance right after they had heard about SRM for the first time. Therefore, opposition might be mainly driven by (negative) emotions in a hot state and could possibly decline after a cooling-off period. This is an important issue since public opposition has far-reaching implications not only for research and deployment of CE but also for future design of climate policy. Understanding public perception of CE and in particular SRM seems critically important given the need for profound societal changes associated with mitigation and adaptation measures in case CE is considered unacceptable by the public.

Our study uses novel panel survey data with more than 3900 observations to analyse the acceptance of SRM in Germany over time. We add to the literature in three respects: First, we provide evidence on how a cooling-off period affects acceptance of SRM and identify potential drivers of change. In particular, we test whether emotions drive acceptance and whether the cooling-off of such emotions changes acceptance over time. Second, we analyse if the length of the cooling-off period affects acceptance. Our three sub-samples allow us to analyse the effect of three different time lengths of cooling-off periods. Third, we test whether not only emotions but also cognitive reflection or impatient behaviour drive changes in acceptance.

Our results provide evidence for the existence of a cooling-off effect. We find that acceptance of SRM increases over time and that the increase becomes larger, the longer the cooling-off period is. For the shortest cooling-off period of one month, 26% of respondents stated a higher level of support for SRM in the second panel wave than in the first. For the longest cooling-off period of 18 months, 45 % of respondents increased their support for SRM. We also find that informing lay people for the first time about SRM leads to strong emotions and that the attenuation of these emotions over time drives the observed increase of acceptance. In addition, other individual specific factors, such as cognitive reflection and impatience, are correlated with the observed changes in acceptance. Higher levels of reflectivity and lower levels of impulsivity lead to smaller changes in acceptance over time.

The remainder of the paper is structured as follows. Section 2 surveys the previous literature and relates it to our research questions. Section 3 outlines the survey design and the data, while section 4 presents the methodological approach. Section 5 describes the results of our empirical analysis. Section 6 discusses and concludes.

2. Previous literature

So far, a cooling-off effect has been observed only in fields other than environmental technologies. Walgrave et al. (2011), for example, find a declining protest cycle in demonstrations against the Iraq war between 2003 and 2006. However, the causes for this decline remain unclear and the authors do not analyse potential cooling-off effects further. Cramton et al. (1999) analyse the cooling-off effect in a field study on wage negotiations between unions and firms in Canada. They find that cooling-off periods reduce the strike incidence of labour unions since some potential strikes settle during the mandatory cooling-off period. Lee (2013) analyses the effect of a mandatory waiting period on the divorce rate in South Korea and finds that a cooling-off period significantly decreases the divorce rate. Faas and Blumenberg (2013) shed light on the public protest against the development of the train station in Stuttgart, Germany, between 2010 and 2012. They use, as we do, data from repeated online surveys. They find that the share of supporters remains nearly the same over time, but that negative emotions decrease over time.¹⁹ However, they do not run a regression analysis and they do not analyse the relation between support and emotions (over time).

Besides these observations from the field, studies analysed the cooling-off effect in controlled laboratory experiments, with students playing ultimatum games, providing mixed evidence. Bosman et al. (2001) show that unfair offers sparked negative emotions in ultimatum games, which then lead to the rejection of unfair offers. However, they find no evidence for the existence of a cooling-off effect: A time delay of one hour between offer and decision did neither affect emotions nor decisions. In contrast, more recently Grimm and Mengel (2011) find that a time-delay of 10 minutes already increases acceptance rates of unfair offers significantly. This effect is more pronounced for men than woman (Espinosa and Kovarik 2015). Similarly, Oechssler et al. (2015) find that a cooling-off period of 24 hours lowers rejection rates in ultimatum games. They also find evidence that the cooling-off effect is more pronounced for impulsive decision-makers (although the effect is not significant).

Regarding the role of emotions, in their laboratory experiments, both Grimm and Mengel (2011) and Oechssler et al. (2015) do not measure emotions explicitly but rather assume that cooling-off is caused by a change in (negative) emotions and that particularly negative emotions drive participants' decisions. Bosman et al. (2001), in contrast, measure respondents' emotions and confirm that negative emotions drive the rejection rate in ultimatum games. Similarly, Wang et al. (2011) and Neo et al. (2013) find that

¹⁹ This result holds for the time prior to the mediation in 2010/2011.

cooling-off reduces negative emotions and decreases the punishment rate in ultimatum games. In addition, Wang et al. (2011) also find that the length of the cooling-off periods influences the punishment rate.

Turning to CE research, quite a number of studies have investigated public perception of CE technologies (e.g., Kniebes et al. 2014; Mercer et al. 2011; Spence et al. 2010). All these studies find that people are generally sceptical about SRM; acceptance rates are, therefore, low. However, there is yet no evidence on the longer-term evolution of public acceptance of SRM or any other CE technique. It is also unclear whether emotions influence acceptance and furthermore whether an emotional cooling-off influences acceptance over time.

Summing up, there is some evidence both from the lab and from the field for the existence of a cooling-off effect. Our study builds upon these findings and contributes to the existing literature in various ways. Novel to the literature, we examine the case of SRM, which is an optimal test case since most people have never heard of SRM and media coverage is still low. Using panel survey data with more than 3900 observations from Germany, we track the acceptance of lay people over time. The two studies that elicited public perception of SRM among the German population provide first insights on public opposition against SRM (Merk et al. 2015) and compare public perception of SRM to two other techniques to counteract climate change (Kniebes et al. 2014). Neither these two studies and nor any of the other studies on public perception of CE provide evidence on the longer-term evolution of perception.

There is, therefore, also no consistent evidence on how a cooling-off period and in particular its length affects acceptance. We, therefore, analyse how different lengths of cooling-off periods affect a respondent's acceptance. For doing so, we use a comprehensive regression framework to quantify the effect of cooling-off on the change in acceptance over time. Also systematic evidence on the drivers of change is very limited. For example, none of the previous studies analyse the influence of positive emotions. We, therefore, analyse the influence of both positive and negative emotions and control for other factors such as cognitive reflection and condition on potentially important individual-specific factors that might drive a respondent's change in acceptance.

3. Data and survey design

Our study uses data from two waves of three representative online surveys on SRM. We conducted the first wave at three points in time (survey (1) in July 2014, survey (2) in August 2013 and survey (3) in December 2012) to investigate potential differences in the rate of change depending on the time-span between the first and the second survey. In the following, we refer to the first wave of each survey as date 't-1' surveys. All three surveys were repeated with the same respondents in August 2014. In the following, we refer to the second wave of each survey date 't' surveys. All respondents aged 18 or above

were recruited through a professional online panel. They were sampled using quotas for gender, age and place of residence (federal state). In total, our working sample in t-1 includes 3905 observations. In t, 1934 respondents repeated the surveys.

All surveys of a wave were structured identically and differed only with respect to the time of elicitation. The surveys were structured as follows:

In the first part of the surveys conducted in t-1, we elicited respondents' perception of the seriousness of climate change and their ecological values. The ecological values were measured by five items from the New Ecological Paradigm Scale (NEP, Dunlap et al. 2000). Then, respondents were asked about their awareness of SRM, i.e., whether they had heard (a little) about SRM before or not.

In the second part of the surveys in t-1, all respondents were shown an information video about SRM (the content is provided in appendix). The video provided respondents with information on SRM using animated graphics. The animations were supported by verbal explanations spoken by a professional radio presenter. Respondents who were not able to listen to or to play the video were excluded at the beginning of the survey. It was not possible to fast-forward the video or skip parts of it. The video first provided respondents with information on anthropogenic climate change and its likely consequences and explained the two-degree target. The video then introduced mitigation, adaptation and SRM as three possibilities of tackling climate change. Subsequently, the video explained SRM in more detail, i.e., its underlying mechanisms and its impact on climate change, the current state of research and the potential benefits and risks of SRM. The information was based on peer-reviewed papers and scientific reports (taken from, e.g., Crutzen 2006; IPCC 2007; IPCC 2012; Royal Society 2009). External experts checked the information for correctness and clarity. After watching the video, we asked respondents about the clarity of the information provided on the video. For each survey, more than 98% of the respondents indicated that they had understood the video well or very well.

In the third part of the surveys in t-1, we proceeded to elicit the respondents' acceptance of SRM. Respondents were asked about their level of agreement (or otherwise) 'to using SRM to counteract climate change'. Potential answers ranged from 1 ('strongly disagree') to 4 ('strongly agree'). Next, we elicited respondents' attitude toward a measure such as 'SRM is the easy way out'. We also measured trust in various actors or institutions to act in the interest of society and the environment. Thereafter, we elicited respondents' egoistic, altruistic and security values. These values were measured using items from the Schwartz Personal Value Questionnaire (PVQ5X, Schwartz et al. 2012, Beyerlein personal communication). Subsequently, we then elicited respondents' emotional response to SRM. Respondents were asked how strongly they experienced various positive reactions (delight, satisfaction, hopefulness, relief) and negative responses (worry, fear, sadness, anger, annoyance) when thinking about SRM, using a scale from 1 ('not at all') to 4 ('strongly'). In our analysis, we summarised negative and positive

emotions in a composite index. Next, respondents of survey (1) completed the cognitive reflection test (Frederick 2005) a test on their level of impulsivity using the short version of the Barratt Impulsiveness Scale (Patton et al. 1995; Steinberg et al. 2013). The cognitive reflection test (CRT) indicates whether a respondent is a rather intuitive (low CRT score) or a rather reflective person (high CRT score). Finally, we collected information from all respondents on their personal characteristics such as gender and education.

For the repeated surveys conducted at time t , we first showed respondents a screenshot of the video that was embedded in the initial surveys at $t-1$ and asked them whether they could remember seeing the video in $t-1$. Respondents who did not remember seeing the video on SRM were excluded from the survey in t . The remaining respondents proceeded and repeated most of the questions from the surveys in $t-1$. In addition, we asked respondents whether they informed themselves about SRM and/or on climate change between $t-1$ and t . We also asked them to state how their level of knowledge on SRM changed between $t-1$ and t . Finally, we repeated the questions on the personal characteristics.²⁰ Table A-1 in the appendix reports all survey items used in our analysis and the scales on which they are measured.

4. Methodology

Our analysis proceeds in three steps. In the first step, we use a descriptive analysis to compare respondent i 's acceptance and emotions for the three surveys in $t-1$ (either July 2014, August 2013 or December 2012) and t (August 2014). In the second step, we use a regression framework to identify potential drivers of a respondent's change in acceptance. In particular, we add respondents' emotions to the regression framework to test whether emotions drive observed changes in acceptance (research question 1). We also test for the influence of personal characteristics and socio demographic factors. In a third step, we restrict our analysis to survey (1), and test whether cognitive reflection or impatient behaviour drives the change in acceptance (research question 2).

To analyse determinants of a respondent's change in acceptance (research question 1), we first estimate the following equation:

$$(I) \quad \Delta acceptance_i = \alpha + \beta survey_i + \gamma \Delta X_i + \delta Y_{i,t-1} + \varepsilon_{i,t}$$

with

$$\Delta acceptance_i = acceptance_{i,t} - acceptance_{i,t-1}$$

and

²⁰ Since it can be assumed that a person's cognitive reflection and impulsivity does not change over the period we investigate, the questions were not repeated for respondents of survey (1).

$$\Delta X_i = X_{i,t} - X_{i,t-1}$$

In equation (I) the dependent variable $\Delta acceptance$ is defined as the difference between acceptance at time t and $t-1$. Acceptance measures respondent i 's level of acceptance. It takes ordered values from 1 ('strongly disagree') to 4 ('strongly agree'). Accordingly, a positive (negative) value of $\Delta acceptance$ means that individual i 's acceptance of SRM has increased (decreased) between $t-1$ and t . The sign of $\Delta acceptance$ does not make a statement about the level of acceptance but only about its change over time. For instance, $\Delta acceptance$ might be positive even if an individual still somewhat disagrees with the use of SRM at time t . The vector $survey$ is a set of dummy variables for the different surveys. These dummies take into account that the date of the first elicitation differs between surveys. ΔX is the change in emotions (negative and positive) between t and $t-1$. Y is a vector of personal characteristics measured in $t-1$ (acceptance, negative emotions, positive emotions, perceived seriousness of climate change, ecological values (NEP), egoistic values, altruistic values, attitude towards SRM, gender and education).

To investigate the effect of cognitive reflection and impulsivity on the change in acceptance (research question 2), we restrict the analysis to respondents of survey (1) and estimate the following equation:

$$(II) \quad \Delta acceptance_i = \alpha + \gamma \Delta X_i + \delta Y_{i,t-1} + \vartheta Z_i + \varepsilon_{i,t}$$

Unlike equation (I), equation (II) contains the additional vector Z capturing cognitive reflection and impulsivity-non-patience measured in $t-1$.

In all cases, the responses for ecological values (NEP), egoistic values, altruistic values and impulsivity are standardised indices. Variable definitions can be found in table A-1 in the appendix and summary statistics can be found in table A-2 in the appendix.

5. Results

5.1 Descriptive results

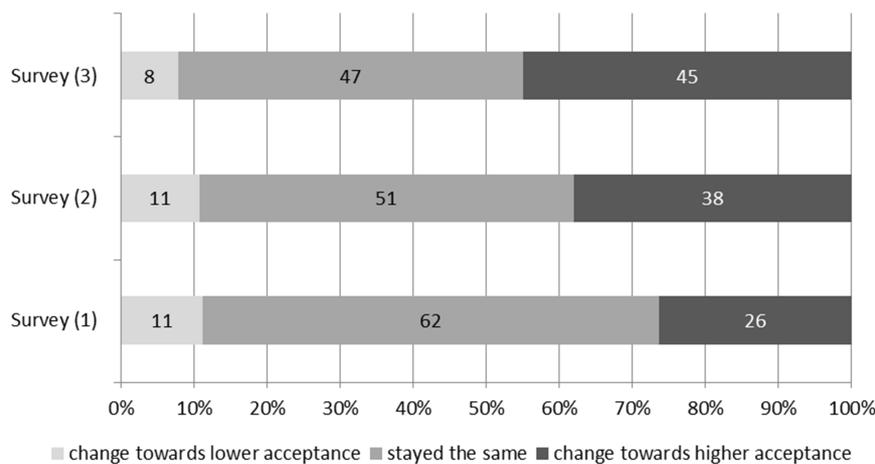
We find for all three surveys that the acceptance of SRM differs significantly between the first and the second elicitation (T-tests reveal p values of 0.000 for all three surveys). The average acceptance of SRM increased between the first elicitation in $t-1$ (either July 2014 for survey (1), August 2013 for survey (2) or December 2012 for survey (3)) and the second elicitation in t (August 2014). However, the size of the increase varies strongly between the three surveys. For survey (1), the share of respondents who agree with the use of SRM increased from 28% to 36% between July 2014 and August 2014. For survey (2), the share of respondents who agree with the use of SRM increased from 27% to 47% between August 2013 and August 2014. For survey (3), the share of respondents who agreed with the use of SRM increased from 25% to 45% between December 2012 and August 2014.

These results show first that the average acceptance of SRM is similar for all three surveys at the initial date of elicitation in t-1 (25%-28%). Thus the different initial date of elicitation does not seem to influence the acceptance of SRM in t-1 strongly. Second, the average acceptance increases between the first and the second date of elicitation. This result holds for all three surveys. Third, the increase in acceptance between the first and the second date of elicitation is greater for longer time gaps between t-1 and t. The increase is only 7% for survey (1) with the shortest time span and 20% each for surveys (2) and (3).

We next calculate the share of respondents whose level of acceptance increased over time, decreased or remained unchanged. For doing so, we subtract the stated acceptance in t from the stated acceptance in t-1. Recall that acceptance takes ordered values from 1 ('strongly disagree') to 4 ('strongly agree'). Positive values therefore indicate an increase in the level of acceptance, whereas negative values indicate a decrease. Figure 1 shows the share of respondents that changed their level of support for SRM between t and t-1.

We find for survey (1) that 26% of respondents stated a higher level of support for SRM in August 2014 than in July 2014. Thus, more than a fourth of respondents increased their support for SRM within a month of time. For survey (2), 38% of respondents increased their support for SRM. Here, the time gap between the two dates of elicitation was one year. For survey (3), 45 % of respondents increased their support for SRM. For survey (3), the time gap was almost 1½ years. Thus we find again that the increase of support is greater the longer the time gap between t and t-1. In contrast, the share of respondents whose support for SRM decreased is similar for all three surveys (11% for survey (1), 11% for survey (2) and 9% for survey (3)).

Figure 1: Change in acceptance between t and t-1

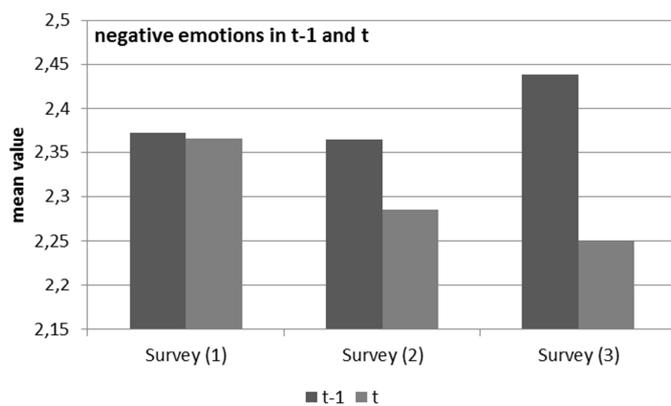


Not only acceptance changed between t-1 and t, also respondents' emotions towards SRM changed over time. Figure 2 illustrates that the negative emotions of respondents towards SRM decreased over

time. The decrease in negative emotions is strongest for survey (3) (-0.2065 points) and smallest for survey (1) (-0.0036 points). This mirrors our findings on the increase in acceptance between t and t-1.

Our findings on the change of positive emotions towards SRM are ambiguous. While positive emotions towards SRM increased over time for survey (1) and survey (2), positive emotions decreased for survey (3). Overall, the summary statistics of positive emotions reveal that respondents do not feel very positive about SRM at any time. The average respondent in all three surveys disagreed at any time with having positive feelings about SRM. Table A-2 provides summary statistics for negative emotions in t-1 and t.

Figure 2: Negative emotions towards SRM in t and t-1



Note: Respondents were asked how strongly they experienced various negative responses (worry, fear, sadness, anger, annoyance) when thinking about SRM, using a scale from 1 ('not at all') to 4 ('strongly'). In our analysis, we summarised negative emotions in a composite index.

5.2 Regression analysis

5.2.1 Determinants of change in acceptance

Building on our descriptive findings, we run OLS regressions to determine the strength of the effect of change in acceptance separately for each survey and to determine potential drivers of this effect, such as a change of emotions over time. Table 1 summarizes the regression results.

We find that the change in acceptance is smallest for survey (1), for which acceptance increases only by 0.1760 points between July 2014 and August 2014 (from 1.9792 points to 2.1553 points).²¹ The effect for survey (2) is significantly higher (0.3802 points) and strongest for survey (3) (0.4410 points) (column 1). These numbers mirror our descriptive findings from section 5.1.

In the next step, we add sequentially potential determinants to our regression in order to analyse the drivers of the change in acceptance. We start by adding the change in emotions over time to the regression framework (column 2). We do so to test whether an emotional cool down led to a change in

²¹ Acceptance measures respondent *i*'s level of acceptance. It takes ordered values from 1 ('strongly disagree') to 4 ('strongly agree').

acceptance - or in other words, whether the stated acceptance in t-1 was driven by an emotional overreaction (research question 1). We find that the change in both (negative and positive) emotions over time is a significant determinant. Respondents who felt less negative (more positive) about SRM in t than in t-1 were also more willing to accept the use of SRM in t than in t-1. Thus, we find clear support for the existence of a cooling-off effect of emotions.

In the next step, we add the initial values in t-1 of acceptance and emotions to our regression framework (column 3). We do so to control for the initial level of acceptance and emotions in t-1 as the change in acceptance might be greater for respondents that stated more extreme values in t-1. We find that the starting value of acceptance has a statistically significant negative effect on the change in acceptance. Respondents who stated a higher level of acceptance in t-1 show a smaller increase in acceptance between t and t-1. The same is true for respondents who stated strong negative emotions towards SRM in t-1. In contrast, respondents who felt positive about SRM in t-1 show a stronger increase in acceptance between t and t-1. The change in emotions remains a statistically significant determinant of the change in acceptance. Therefore, we find that not only the change in emotions but also the initial levels of emotions and acceptance drive the change in acceptance over time.

In the next step, we add other potential determinants such as values or personal characteristics to our regression framework (column 4). We find that the perception of seriousness of climate change determines the change in acceptance over time. Respondents who perceived climate change as more severe in t-1 show a significantly stronger increase in acceptance between t-1 and t.

Similarly, respondents who stated a higher agreement with the statement that 'SRM is the easy way out' in t-1 show a significantly stronger increase in acceptance. The acceptance of more altruistic respondents also increased over time. In contrast, we do not find a corresponding effect for egoistic or environmental friendly (high NEP score) respondents. With respect to the socio demographic variables, we find that the level of acceptance increased more for women than for men. Education has a significant impact on the change in acceptance over time. The increase in acceptance is lower for respondents with higher levels of education.

In a sensitivity analysis we added two more control variables that indicate whether respondents informed themselves about SRM or climate change between t-1 and t, and we also controlled for respondents' change in knowledge about SRM between t-1 and t. However, these additional control variables remained statistically insignificant (results not shown). Therefore, changes in knowledge about SRM or climate change do not drive the observed change in acceptance.

Overall, we find that the change in acceptance over time varies with individual specific factors. Our regression results support the existence of cooling-off. The cooling-off of negative emotions is an important driver of the observed increase in acceptance over time. The same also holds for changes in

positive emotions. Other factors, such as gender or education, also affect the change of acceptance over time.

Table 1: OLS regression results

Change in Acceptance	(1)	(2)	(3)	(4)
Constant	0.1760*** (0.0264)	0.1667*** (0.0253)	1.4138*** (0.0951)	0.7499*** (0.1745)
Survey (1)	omitted	omitted	omitted	omitted
Survey (2)	0.2042** (0.0661)	0.1219* (0.0574)	0.0894* (0.0457)	0.0748* (0.0499)
Survey (3)	0.2650*** (0.0601)	0.2504*** (0.0553)	0.1330** (0.0437)	0.1407*** (0.0426)
Change in negative emotions		-0.2340*** (0.0303)	-0.2618*** (0.0631)	-0.2816*** (0.0253)
Change in positive emotions		0.3714*** (0.0436)	0.4807*** (0.0379)	0.4792*** (0.0361)
Acceptance t-1			-0.6868*** (0.0316)	-0.7140*** (0.0302)
Negative emotions t-1			-0.2462*** (0.0248)	-0.2958*** (0.0254)
Positive emotions t-1			0.4545*** (0.0395)	0.4471*** (0.0379)
<i>Attitudes</i>				
Climate change seriousness t-1				0.1496*** (0.2475)
SRM is the easy way out t-1				0.0397* (0.0217)
<i>Values</i>				
NEP t-1				-0.0208 (0.0361)
Altruistic t-1				0.0985*** (0.0339)
Egoistic t-1				0.0198 (0.0258)
<i>Demographics</i>				
Female				0.0671* (0.0327)
Education				-0.0418*** (0.0117)
Observations	1118	1118	1118	1118
Adjusted R^2	0.0216	0.1756	0.4679	0.5055

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

5.2.2 The effect of cognitive reflection and impulsivity

In the following our analysis focuses on responses to survey (1) which contains data on respondents' cognitive reflection and impulsivity. We use this information to test whether more rational and reflective or more impatient and impulsive respondents behave differently regarding the change in acceptance over time (research question 2). The change in acceptance might not only be driven by an emotional component but also by a person's level of rationality or impulsivity. Table 2 shows the results.

In a first step, we add cognitive reflection and impulsivity to our regression framework (column 2). We find that the change in negative and positive emotions, the initial levels of negative and positive emotions and acceptance remain significant determinants of a change in acceptance. In addition, cognitive reflection and impulsivity also have a significant impact. Acceptance of more reflective respondents (higher CRT score) increases less than that of less reflective ones. Also the acceptance of more patient respondents increased significantly less than that of impatient respondents. Overall, we therefore find that higher levels of reflectivity as well as lower levels of impulsivity lead to smaller changes in acceptance over time. In addition, we also confirm the results from table 1, namely that emotional reactions drive the change in acceptance over time.

Table 2: OLS regression results for survey (1)

Change in Acceptance	(1)	(2)	(3)
Constant	1.2676*** (0.1372)	1.7486*** (0.1827)	1.1030*** (0.2484)
Change in negative emotions	-0.2192*** (0.0378)	-0.2206*** (0.0365)	-0.2507*** (0.0350)
Change in positive emotions	0.3898*** (0.0581)	0.3694*** (0.0555)	0.3828*** (0.0535)
Acceptance t-1	-0.5988*** (0.0406)	-0.6181*** (0.0393)	-0.6517*** (0.0393)
Negative emotions t-1	-0.2164*** (0.0342)	-0.2246*** (0.0345)	-0.2785*** (0.0348)
Positive emotions t-1	0.3899*** (0.0573)	0.3782*** (0.0552)	0.3874*** (0.0542)
Cognitive reflection t-1		-0.0887*** (0.0205)	-0.0655*** (0.0203)
Impulsivity t-1		0.1008** (0.0365)	0.1024** (0.0364)
<i>Attitudes</i>			
Climate change seriousness t-1			0.1423*** (0.0328)
SRM is the easy way out t-1			0.0370 (0.0287)
<i>Values</i>			
NEP t-1			-0.0175 (0.04738)
Altruistic t-1			0.0812* (0.0457)
Egoistic t-1			0.0205 (0.0356)
<i>Demographics</i>			
Female			0.0742* (0.0440)
Education			-0.0325** (0.0160)
Observations	613	613	613
Adjusted R^2	0.3519	0.3779	0.4124

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

6. Discussion and conclusion

Political actions are often driven by public opinions. There are many recent examples where public protests led to a change of policies (Burstein 2003). However, public opposition might at times be only temporary phenomena, especially if it is driven by negative emotions that cool off over time. While such cooling-off in emotions has been documented for ultimatum games in the laboratory, there is yet no consistent empirical field evidence on how a cooling-off period and in particular its length affects public opposition and what the drivers of the cooling-off effect are. There is also no evidence on the evolution of public opposition against environmental technologies.

This paper uses novel panel survey data with more than 3,900 observations to shed light on the development of public opposition against solar radiation management (SRM), a controversially discussed climate engineering technology that counteracts climate change by technically cooling down the planet. The case of SRM is particularly interesting to test for the interplay of emerging perceptions and emotions since most people have never heard of SRM and media coverage is still low (Merk et al. 2015; Mercer et al. 2011). We track the acceptance of lay people over time and test whether temporary emotions drive public opposition against SRM.

Our results provide evidence for the existence of a cooling-off effect. We find that acceptance of SRM increases over time and that the increase becomes larger the longer the cooling-off period. We find further that informing lay people for the first time about SRM leads to strong emotions and that the change in emotions over time drives the observed increase of acceptance. Interestingly, changes in negative and positive emotions are both equally important in driving the increase in acceptance. We also find, in line with Oechssler et al. (2015), that the cooling-off effect is more pronounced for more impulsive respondents. In addition, we show that not only lower levels of impulsivity but also higher levels of cognitive reflection lead to smaller changes in acceptance over time.

Overall, our results suggest that initial opposition towards SRM does not need to be permanent. It is therefore important to elicit public attitudes over a longer time period. Before governments make a final decision on the use of a technology, citizens should be given time to stabilize their opinion.

7. References

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8. Appendix

Table A-1: Survey items

Questions and items		Response scale
Acceptance	We should use SRM to counteract climate change.	strongly disagree (1) - strongly agree (4)
Emotions	When thinking of SRM, how strong do you feel the following emotions? Worry, fear, sadness, anger, annoyance, delight, satisfaction, hopefulness, relief	strongly disagree (1) - strongly agree (4)
Seriousness of climate change	Climate change is a serious problem.	strongly disagree (1) - strongly agree (4)
Attitude	SRM is the easy way out.	strongly disagree (1) - strongly agree (4)
Ecological values	The earth is like a spaceship with very limited room and resources. Humans were meant to rule over the rest of nature. The balance of nature is very delicate and easily upset. Humans will eventually learn enough about how nature works to be able to control it. If things continue on their present course, we will soon experience a major ecological catastrophe.	strongly disagree (1) - strongly agree (4)
Altruistic values	She thinks it is important that every person has equal opportunities in life. She works to promote peace among diverse groups. Protecting society's weak and vulnerable members is important to her. Caring for the well-being of people she is close to is important to her.	strongly disagree (1) - strongly agree (4)

Questions and items (<i>continued</i>)	Response scale
<p>Egoistic values</p> <p>She wants people to do what she says. Being wealthy is important to her. It is important to her to be the one who tells the others what to do. It is important to her to be the most influential person in any group.</p>	<p>strongly disagree (1) - strongly agree (4)</p>
<p>Cognitive reflection</p> <p>A bat and a ball cost \$1.10 in total. The bat costs \$1.00 more than the ball. How much does the ball cost? If it takes 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? In a lake there is a patch to cover the entire lake, how long would it take for the patch to cover half of the lake?</p>	
<p>Impulsivity</p> <p>I plan tasks carefully. I am self-controlled. I am a careful thinker. I say things without thinking.*</p>	<p>rarely/never (1) – almost always/always (4)</p>
<p>Knowledge</p> <p>Have you informed yourself about climate change since the first survey? Have you informed yourself about SRM since the first survey? Do you know more or less about SRM today than you did at the time of the first survey?</p>	<p>no (1) - yes (2) no (1) - yes (2) a lot less (-1) – a lot more (1)</p>
<p>Education</p> <p>What is your highest degree?</p>	<p>No school degree (1) – higher education entrance certificate (6)</p>

* Reverse score questions

Table A-2: Summary statistics

Variables	Domain	Survey (1) N = 676		Survey (2) N = 213		Survey (3) N = 229	
		mean	standard deviation	mean	standard deviation	mean	standard deviation
Acceptance (t-1)	1-4 ^a	1.979	0.9073	1.9671	0.9234	1.8733	0.9303
Acceptance (t)	1-4 ^a	2.155	0.8833	2.3474	0.8695	2.3144	0.8869
Change in acceptance		0.1760	0.6864	0.3802	0.8854	0.4410	0.8177
Negative emotions (t-1)	1-4 ^a	2.3724	0.8418	2.3653	0.8384	2.4390	0.8604
Negative emotions (t)	1-4 ^a	2.3666	0.8704	2.2856	0.8782	2.2505	0.8330
Change in negative emotions		-0.0036	0.6904	-0.0918	0.7618	-0.2065	0.8295
Positive emotions (t-1)	1-4 ^a	1.5265	0.6994	1.5305	0.7284	1.6699	0.7496
Positive emotions (t)	1-4 ^a	1.5469	0.7096	1.7226	0.8112	1.6022	0.7222
Change in positive emotions		0.0226	0.5423	0.1885	0.7402	-0.0662	0.5771
Seriousness of climate change (t-1)	1-4 ^a	3.4792	0.7390	3.5258	0.7558	3.4803	0.7409
Attitude: SRM is the easy way out (t-1)	1-4 ^a	3.1553	0.8385	3.3004	0.7973	3.1266	0.9112
Ecological values (t-1)	1-4 ^a	0.7542	0.5326	0.7249	0.4848	0.7081	0.5313
Altruistic values (t-1)	1-4 ^a	3.3836	0.5096	3.4178	0.4795	3.3158	0.5386
Egoistic values (t-1)	1-4 ^a	2.0636	0.6415	2.1760	0.6699	2.3129	0.6685
Cognitive reflection test (t-1)	0-3 ^b	1.0799	1.0989				
Impulsivity non planning (t-1)	1-4 ^c	-3.0655	0.5759				
Informed about climate change btw. (t-1) and (t)	1 (no); 2(yes)	1.2781	0.4483	1.3521	0.4787	1.4235	0.4952
Informed about SRM btw. (t-1) and (t)	1 (no); 2(yes)	1.1538	0.3610	1.131	0.3386	1.1179	0.3232
Change in knowledge about SRM between (t) and (t-1)	-1(decrease)-1(increase)	0.7889	0.6160	0.5652	0.8340	0.5483	0.8430
Education	1 (no)-6 (highest level)	4.5502	1.3905	4.6384	1.4194	4.6462	1.3284
Female	0 (Male); 1 (Female)	0.4866	0.5001	0.4460	0.4982	0.4192	0.4945

Note: ^a Response scale ranges from strongly disagree (1) – strongly agree (4). ^b The variable counts the number of correct answers ranging from 0 (no correct answer) to 3 (all correct).

^c Response scale ranges from rarely/never (1) to almost always/always (4), reversed item.

Information provided in the SRM video

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere (e.g., CO₂) ensure that some of this warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals and plants to live on.

Since the start of industrialisation around 1850, people have emitted a very large amount of greenhouse gases by burning coal, oil and gas. These gases trap more heat in the atmosphere and cause a gradual increase in average global temperature.

Since 1900, global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in average global temperature should not exceed two degrees compared to pre-industrial levels. The attempt to ensure that this is the case is referred to as the two-degree target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To achieve the two-degree target, the current level of emissions would have to be cut by more than half by 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of severe precipitation events in many regions. It is likely that in future more areas will be affected by extended droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the CO₂ emitted is absorbed by the ocean, thus causing ocean acidification.

There are different ways of dealing with climate change.

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is to reduce global temperature by means of solar radiation management (SRM).

Via SRM some sunlight is reflected before it can warm the Earth. This can be accomplished by, for example, spraying sulphate particles into the atmosphere at a high altitude.

A similar phenomenon can be observed in nature. When large volcanoes erupt, similar particles are distributed across wide areas of the Earth's atmosphere, cooling the Earth.

The particles remain in the higher regions of the atmosphere for approximately two years. To prevent the Earth from heating up again, spraying would have to be continued until the cause of global warming has been removed. Because CO₂ remains in the atmosphere for a very long time, SRM might have to be used for several centuries. However, using SRM will not stop ocean acidification.

Currently, the risks, benefits and feasibility of SRM are the object of research.

The use of SRM entails benefits as well as risks. One of the benefits is that it would be a quicker way of counteracting global warming than cutting down on greenhouse gas emissions. This would buy additional time to remove the cause of climate change, i.e., the high concentration of greenhouse gases in the atmosphere. Massive and irreversible changes in the climate could be stopped before too much damage has been done. Furthermore, it would be possible to stop climate change even if certain countries decide not to reduce their greenhouse gas emissions. Deploying SRM would be less expensive than reducing the consumption of fossil fuels.

The risks include a change in the amount of precipitation in most regions. Arid regions in particular would have to cope with even less rain. If the deployment of SRM were suddenly stopped, global temperature would rise abruptly. The speed of this rise in temperature would lead to severe problems for humans and the environment. Because possible side effects would be trans-boundary, the use of SRM could cause international conflicts. Once in use, SRM might have a negative effect on people's motivation to change their lifestyle: greenhouse gas emissions would continue to increase. Other hitherto unknown and unforeseeable risks might also arise.

Paper V: Not in my backyard: CCS storage sites and public perception of CCS

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Abstract

Carbon capture and storage (CCS) is a technology that counteracts climate change by capturing atmospheric emissions of CO₂ from human activities, storing them in geological formations underground. However, CCS also involves major risks and side effects, and faces strong public opposition. Recently, the whereabouts of 408 potential CCS storage sites in Germany have been released. Using detailed survey data on the public perception of CCS, I quantify how living close to a potential storage site affects the acceptance of CCS. I also analyse the influence of other regional characteristics on the acceptance of CCS. I find that respondents who live close to a potential CCS storage place have significantly lower acceptance rates than those who do not. Living in a tourism or mining region also markedly decreases acceptance.

Note: A modified version of this paper is published as: Braun C, 2016. Not in my Backyard: CCS Storage Sites and Public Perception of CCS. Kiel Working Paper, 2028, Kiel Institute for the World Economy.

1. Introduction

Carbon capture and storage (CCS) is a technology that removes atmospheric emissions of CO₂ from human activities and transports it to a storage site. The large-scale use of CCS from 2030 onwards is considered a key factor for reaching the 2°C target (IPCC 2014). In fact, all available projections suggest that the use of CCS is required to reach the 1.5°C global warming target, recently agreed on the 2015 United Nations Climate Change Conference in Paris. It is expected that CCS will become cost competitive soon and can then be applied on a large-scale (International Energy Agency 2015). However, local residents have, in the past, often fiercely opposed CCS pilot tests in Germany. These local tests gather information on the benefits and risks of CCS and are thus necessary before CCS can be applied on a large scale. It is therefore important to understand what drives local acceptance of CCS and, in particular, how the prospect of a CCS site in the neighbourhood affect local acceptance. Against this background, this paper analyses regional factors that shape the acceptance of CCS in Germany.

CCS captures CO₂ from the industrial combustion of fossil fuels before it enters the atmosphere. The captured CO₂ is first compressed and then transported to long-term storage sites. Scientists consider geological formations such as saline aquifer formations and depleted gas fields as suitable long-term storage sites. In Germany, the whereabouts of all 408 such potential saline aquifer CCS storage sites have been released in 2011 (German Federal Institute for Geosciences and Natural Resources, Greenpeace 2011). These potential storage sites are very unequally distributed across Germany. In fact, more than half of the sites are located in the northern states of Schleswig-Holstein and Lower Saxony (see Figure 1).

Putting a CCS storage site in place poses a typical public good distribution conflict: the risks of storing CCS underground are borne locally, while the benefits accrue to everyone (Rickels et al. 2011; Rosa 1988). In general, climate change and its mitigation are, by definition, public goods, as they are non-rival and non-excludable. In particular, actors who do not participate in climate mitigation efforts cannot be effectively excluded from the benefits of mitigation (IPCC 2012; Barrett 2007; Milinski et al. 2008). This also holds for CCS, as everyone benefits from the CO₂ reduction achieved by CCS. In contrast, only local actors bear the risks of CO₂ leaks from underground CCS storage sites. The tension between local risks and global benefits causes a public good distribution conflict (Rosa 1988). This distribution conflict might induce residents to develop a ‘not in my Backyard’ (NIMBY) attitude, so that residents who live close to a CCS storage site show lower levels of acceptance.²²

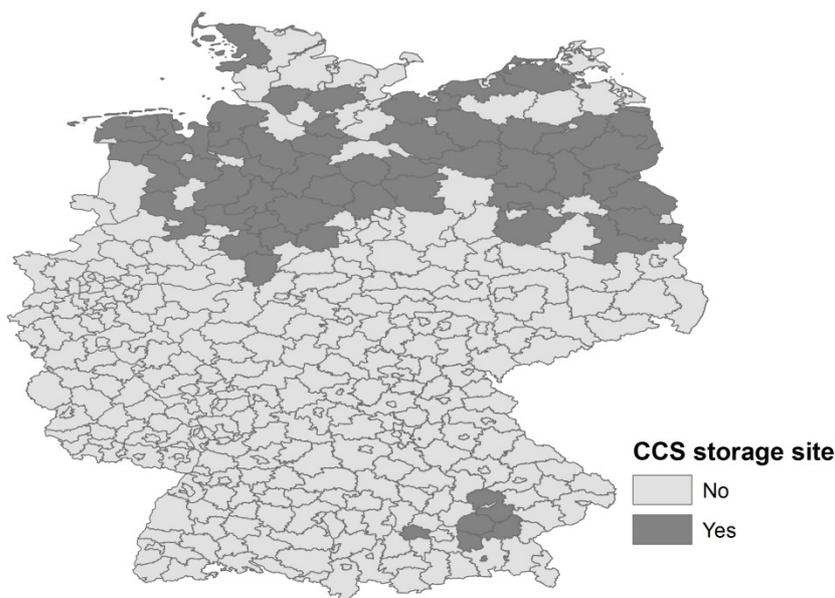
²² The term ‘NIMBY’ (not in my backyard) is widely used in the literature to describe the phenomenon that support for a technology decreases with increasing proximity to its location (see e.g., Frey and Oberhölzer-Gee 1997; Johnson and Scicchitano 2012).

In this paper, I quantify the effect of potential CCS storage sites and other regional characteristics on the acceptance of CCS in Germany, and shed light on the potential channels through which the NIMBY effect operates. The paper is the first to analyse the NIMBY effect for CCS in Germany. Since Germans are more sceptical towards potentially risky technologies, such as nuclear energy or CCS, than other Europeans (European Commission 2011), Germany is an especially interesting case to consider. More generally, the paper is the first to analyse the acceptance of respondents who indeed live close to a potential CCS storage site and might thus be directly affected by CCS in the future.

In my empirical analysis, I combine novel survey data on the public perception of CCS in Germany with data on the exact locations of all potential CCS storage sites. I find that respondents who live close to a potential CCS storage site have indeed significantly lower acceptance rates than those who do not. This effect is robust to the inclusion of other potential determinants of CCS acceptance at both the individual and the regional level. Living in a tourism or coal mining region also markedly decreases acceptance. Finally, I present suggestive evidence that living close to a CCS storage site reduces acceptance by increasing the perceived risk of CCS and decreasing the perceived benefits.

The remainder of the paper is structured as follows. Section 2 surveys the previous literature and relates it to my research questions. Section 3 outlines the survey design and the data, while section 4 presents the empirical approach. Section 5 describes the main results of the empirical analysis, and section 6 discusses additional robustness checks. Section 7 concludes.

Figure 1: Potential CCS storage sites in Germany



Source: Own presentation with data from Knopf et al. (2010), German Federal Institute for Geosciences and Natural Resources.

2. Literature review

There exists a growing literature on public perception of CCS. However, most of these studies do not consider regional variation in acceptance rates, and thus do not analyse regional determinants of CCS.

There are large cross-country differences in public acceptance of CCS, and existing studies report both negative and positive attitudes towards CCS. Hund and Greenberg (2011), for instance, find that respondents in the US state of Illinois perceive the economic benefits of CCS as more important than their potential risks. In contrast, respondents in Europe typically raise concerns about the risks of CCS (European Commission 2011), but perceptions differ across countries. Romanians, for instance, accept CCS much more readily than Germans (Pietzner et al. 2011). Even within Germany, the few existing case studies suggest that the acceptance of CCS differs significantly across regions (Dütschke 2011; Fishedick et al. 2008). Dütschke (2011), for example, shows that local residents in the East German town of Ketzin perceive CCS rather positively, whereas residents in the East German town of Beeskow strongly oppose CCS. However, so far no study has analysed variations in local acceptance rates for Germany as a whole.

In general, previous studies show that individual-specific attitudes such as the perception of climate change or trust in institutions influence the acceptance of CCS (Kniebes et al. 2014; Terwell et al. 2009). Concerns about risks such as leakage, over-pressurization of the reservoir, and the fear of negative effects on the natural environment and public health reduces acceptance of CCS (Krause et al. 2014; Ashworth et al., 2010; Palmgren et al. 2004; Shackley et al. 2005; Wallquist et al. 2010). For countries other than Germany, safety concerns about local storage sites and falling local property prices have been shown to decrease acceptance, pointing towards a regional dimension of CCS (Krause et al. 2014; Terwel and Daamen 2012). In contrast, potential economic benefits of CCS facilities increases support for locating such facilities in the neighbourhood (Krause et al. 2014; Hund and Greenberg 2011). However, Krause et al. (2014) and Hund and Greenberg (2011) do not explicitly distinguish between the expected benefits and risks of CCS storage sites, CCS power plant and pipelines. This might lead to biased results as CCS storage sites bear most local risks, such as leakage, whereas CCS power plants also generate economic benefits by, for instance, creating new jobs.

A possible explanation for regional variation in the acceptance of CCS is the so-called 'not in my Backyard' (NIMBY) effect. The NIMBY effect describes the phenomenon that residents oppose a technology, for example a windfarm, if it is too close to their homes. Often, these residents indicate that they generally support the technology, but only if it is located far away from their homes (i.e., not in their backyard). In our context, the NIMBY effect suggests that living close to a potential CCS storage site reduces the acceptance of CCS. A few studies have provided evidence that the NIMBY

effect indeed exists for CCS. A Eurobarometer poll found that the public is generally concerned about CCS storage sites within 5 km of their home (European Commission, 2011). In Switzerland, respondents are concerned about CCS storage sites near their home, but even more concerned about CCS power plants and pipelines (Wallquist et al. 2012). For the Netherlands, Huijts et al. (2007) and Terwel and Daamen (2012) provide evidence on the NIMBY effect for CCS. Huijts et al. (2007) use evidence from a case study and compare the perceptions of CCS between two Dutch municipalities. They find that CCS storage sites located in respondents' own residential area were perceived more negatively than sites located somewhere else. Terwel and Daamen (2012) show in a survey experiment that respondents who receive the (hypothetical) information of living above a potential CCS storage site show stronger concerns about the safety risks of CCS.

Krause et al. (2014) uses survey data to analyse the acceptance of CCS in general in the coal-rich US state of Indiana. Respondents reveal rather positive attitudes towards CCS: 80% of the local residents in Indiana support the use of CCS in general. However, a fifth of those who support CCS in general would oppose CCS in their local communities. Therefore, the NIMBY effect seems to reduce local support for CCS. The NIMBY effect only describes that resident often oppose locally applied technologies. It remains silent on the underlying causes, such as changes in risk perception (Devine-Wright 2005; Wolsink 2000; 2006). These underlying causes may play an important role when focussing on the perception of CCS storage sites, which bear severe local risks, but offer global benefits.

Overall, my study contributes to the existing literature in various ways. In contrast to previous studies and novel to literature, I match survey data on the public perception of CCS with geographic information about the location of CCS power plants and potential storage sites. Therefore, I do not ask respondents whether they would (hypothetically) accept a CCS storage site or CCS power plant next to their house or not (as all previous studies did). Rather, I compare perceptions of respondents who are living close to a potential storage site to those who are not. This has the advantage that some respondents in my data are not only confronted by a hypothetical scenario but face the actual risk that their region is selected as a storage site in the future. My paper is also the first to analyse the NIMBY effect for CCS in Germany, and, more generally, the first to study local determinants of CCS acceptance for Germany as a whole (previous studies for Germany have focused only on specific regions). Moreover, and novel to literature, I also distinguish between the effect of CCS storage sites and the effect of industrial power plants that use the CCS technology to capture CO₂. Finally, I analyse potential causal pathways such as a risk perception through which living close to a potential CCS storage site might affect acceptance, and thus shed light on underlying factors that might be responsible for the NIMBY effect.

3. Data and survey design

This paper combines individual-level survey data on the public perception of CCS in Germany with data on the exact location of potential CCS storage sites and CCS power plants as well as with data on other regional characteristics. The survey data contains the county (*Kreis/kreisfreie Stadt*), in which a respondent is living. I use this regional information to identify whether a respondent lives in a county that hosts a CCS storage sites or a CCS power plant, and to link the data with other county characteristics. In the following, I briefly describe the three data sources:

Survey data

I use data from an internet representative online survey which was conducted in August 2013. Respondents aged 18 or above were recruited via an online panel. They are sampled using quotas for the characteristics of gender, age, and state of residence. In total, the working sample includes 332 observations. The average age of respondents is 49 years. Fifty-four per cent of our respondents are male. Thirty per cent of our respondents have a higher education entrance certificate. Table A-1 in the appendix provides summary statistics for the survey data used in my analysis.

The survey was structured as follows. At the beginning, respondents were asked about their level of awareness of the CCS. Afterwards, the survey provided respondents with information on CCS using animated graphics videos. The animations explained the information graphically and were supported by verbal explanations spoken by a professional radio presenter. The video was embedded into the survey.²³ The video first provided respondents with information on anthropogenic climate change and its likely consequences. The video then introduced mitigation, adaption and CCS as three possibilities to address climate change. Afterwards, the video explained CCS in more detail, i.e., CCS's underlying mechanisms and its impact on climate change. The video then informed participants about the current state of research and the potential benefits and risks of CCS. The information was based on peer-reviewed papers and scientific reports (taken from, e.g., IPCC 2005; IPCC 2007; IPCC 2012; UBA 2008). External experts checked the information for correctness and clarity. After watching the video, the survey asked respondents about the clarity of the video. More than 98% of the respondents indicated that they understood the video well or very well.

Afterwards, the survey elicited respondents' acceptance of CCS and asked them about their risk and benefit perception of CCS. Finally, the survey elicited respondents' socio-demographic characteristics, such as gender, age, county of residence and education.

Respondents could refrain from answering. The option 'don't know' was included in every question.

²³ An English translation of the German script of the video is provided in appendix.

Data on CCS storage sites and power plants

The information on the exact location of all potential CCS storage sites in Germany comes from the German Federal Institute for Geosciences and Natural Resources (Knopf et al. 2010). The list contains all 408 potential CCS storage sites, where CO₂ could be stored in saline aquifers. Most CCS storage sites are located in East Freesia and below the mudflats off the coast of Schleswig-Holstein (see Figure 1, section 1). Some are also located close to the cities of Hamburg, Berlin and Munich and in certain parts of North Rhine-Westphalia and West-Mecklenburg Pomerania.

The information on potential storage sites were first released by Greenpeace in February 2011 (Greenpeace 2011). Previously, the locations of potential CCS storage sites were not known. We can thus expect that respondents in our data did not move endogenously to avoid living close to a potential storage site. The announcement of Greenpeace created a lot of media attention in Germany not only in regional newspapers, but also in nationwide newspapers and on TV.

The information on the location and status of CCS power plants comes from the operating companies themselves. At the time of our survey, there were 6 power plants in Germany, which conducted pilot tests with the CCS technology.

Data on regional characteristics of counties

The data on regional characteristics of a county comes from the Regional Database Germany (*Regionalstatistischen Datenkatalog des Bundes und der Länder*). The data is mainly collected by the German Statistical office and publicly available.

4. Methodology

My analysis consists of three steps:

In the first step, I use a regression framework to analyse the effects of living in a county with a potential CCS storage site on an individual's acceptance of CCS. I also analyse the effect of the number of storage sites located in a county and take spill over effect from neighbouring counties into account.

In particular, I estimate the following equation:

$$(I) \quad acceptance_{i,j} = \alpha + \beta X_i + \gamma Y_j + \varepsilon_{i,j}.$$

The dependent variable *acceptance* measures the level of CCS acceptance of individual *i* who lives in county *j*, measured as the level of (dis)agreement with the use of CCS. The variable *acceptance* takes ordered values from 1 ('strongly disagree') to 4 ('strongly agree'). X_i is a vector of individual socio-demographic characteristics (*gender, age, education, income*). *Gender* indicates whether individual *i* is female; *age* measures his or her age; *education* indicates whether individual *i* has a higher

education entrance certificate; *income* measures his or her monthly household net income in Euro.

Y is a vector that contains three different alternative indicators for the regional presence of CCS storage sites. First, Y includes the variable *CCS storage sites*, which indicates whether county j has at least one potential CCS storage site. Second, it includes the variable *Number of CCS storage sites*, which measures the number of CCS storages sites in county j . Third, Y_j also includes the variable *CCS storage site neighbourhood*, which indicates whether county j borders on a county with a CCS storage site. I do not add the three indicators simultaneously but consider them one by one. I restrict the sample to those who do not live in a county with a CCS storage site when considering spill-over effects.²⁴ The coefficient estimate of interest is γ , which is negative if living close to a CCS storage site reduces acceptance.

In a second step, I analyse the influence of other county characteristics on acceptance. For doing so, I add sequentially county characteristics Z to equation (I), and estimate the following equation (II):

$$(II) \quad acceptance_{i,j} = \alpha + \beta X_i + \gamma Y_j + \delta Z_j + \varepsilon_{i,j}.$$

Z_j is a vector that contains county specific characteristics (east, coal mining, CCS power plant, tourism intensity, population density, and Green/Left party). The dummy variable *east* indicates whether a county is located in the eastern part of Germany. The dummy variable *coal mining* indicates whether there is coal mining in a county or not. Previous experiences with coal mining might reduce the acceptance of further interventions in the ground and might therefore decrease the acceptance of CCS.

The dummy variable *CCS power plant* indicates whether there is a power plant in a county that uses CCS technology to capture CO₂. CCS power plants are not necessarily located next to CCS storage sites. The variable *tourism intensity* equals the overnights stays in hotels in a county divided by the population in the same county. Respondents who live in a county with high tourism intensity might report lower levels of CCS acceptance as they might perceive CCS as a threat to the tourism sector of the region.

The variable *population density* equals the population over the area of a county. Respondents who live in highly populated urban areas might perceive CCS differently than respondents who live in the countryside.

The variable *Green/Left party* measures the local vote share of the Green and Left party in the 2013 election for the German parliament. I expect this variable to negatively correlate with local

²⁴ I restrict the sample in this way as almost every individual in my sample who lives in a county with a CCS storage site also lives next to a county with a CSS storage site. Due to multi-collinearity, I am therefore not able to distinguish direct from spill-over effects for individuals who live in a county with a CCS storage site.

acceptance of CCS, since the two parties strongly oppose CCS.

In a third step, I analyse potential causal pathways through which CCS storage sites might affect acceptance. In particular, I hypothesize that living in a county with a potential CCS storage site affects acceptance by changing the awareness of CCS or the perception of risk and benefits. I test these hypotheses by adding measures of awareness and perception to equation (I), and estimate the following equation (III):

$$(III) \quad acceptance_{i,j} = \alpha + \beta X_i + \gamma Y_j + \mu W_i + \varepsilon_{i,j}.$$

W_i is a vector that contains measures of an individual's awareness and perception of CCS (level of awareness, risk perception, benefit perception). The variable *awareness* captures self-reported awareness of CCS. It takes ordered values from 1 if a respondent had never heard about CCS before to 3 if the respondent had heard a lot about CCS before. The variables *risk perception* and *benefit perception* measure how an individual assesses the risk and benefits of CCS. Both variables take ordered values from 1 ('very small') to 4 ('very large'). If indeed the presence of a potential CCS storage site affects acceptance through any of the variables in W , the coefficient estimate of β should be pushed towards zero by including W . At the same time, awareness and/or perception should have a significant effect on acceptance.

I estimate all equations by OLS.²⁵ Standard errors are clustered at the level of administrative districts (*Regierungsbezirke*) to allow for a correlated error terms.

5. Results

In the following, I first present the results on the effect of CCS storage sites on the acceptance of CCS from estimating equation (I). I then present the results from estimating equation (II), which also accounts for other county characteristics. Finally, I shed light on possible causal pathways through which CCS storage sites affect acceptance by presenting the results from estimating equation (III).

Effects of potential CCS storage sites

Table 1 reports the results from estimating equation (I). In the baseline regression in column (1), I use a dummy variable that indicates the existence of at least one CCS storage sites in a county. The result suggests that the acceptance of CCS declines by 0.24 points if an individual lives in a county that has at least one potential CCS storage site. This corresponds to a ten per cent increase relative to the sample mean of 2.54 points. The effect is statistically significant with a p value of 0.081. Furthermore,

²⁵ As a robustness check, I also performed ordered logit regressions. The results, which can be obtained from the author upon request, are very similar to the OLS results.

I find that the acceptance of CCS is 0.31 points higher for females than for males. All other socio-demographic characteristics do not have a statistically significant effect on acceptance.²⁶

In column (2), I replace the dummy variable for CCS storages sites by a continuous variable that counts the number of CCS storage sites in a county. I find that the acceptance of CCS declines by 0.11 points for every additional CCS storage in a county. The effect is statistically significant with a p value of less than 0.001. Overall, therefore, I find clear evidence that living in a county with at least one potential CCS storage site reduces an individual's acceptance of CCS.

Next, I test for the existence of spill-over effects, restricting the sample to those who do not live in a county with a CCS storage site. In particular, I add a dummy to the regression equation that indicates whether an individual lives in a county that borders on a county with a CCS storage site. The results in column (3) suggest that spill-over effects indeed exist. Living next to a county with at least one CCS storage site reduces the level of acceptance by 0.21 points. Therefore, the presence of CCS storages sites appears to reduce the level of acceptance in a relatively large geographic area.

Table 1: OLS regression results equation (I), clustered standard errors

Acceptance	(1)	(2)	(3)
CCS storage site	-0.2375* (0.1322)		
Number of CCS storage sites		-0.1082*** (0.0264)	
CCS storage site neighbourhood			-0.2140* (0.1155)
Female	0.3067** (0.1161)	0.3166** (0.1137)	0.2822** (0.1130)
Age	0.0011 (0.0036)	0.0011 (0.0037)	0.0026 (0.0038)
Education	-0.0955 (0.0995)	-0.1118 (0.1040)	-0.0337 (0.1054)
Income	0.0003 (0.0004)	0.0004 (0.0004)	0.0001 (0.0004)
Constant	2.3536*** (0.2295)	2.3433*** (0.2290)	2.3504*** (0.2314)
Observations	332	332	282
R ²	0.0340	0.0422	0.0324

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

²⁶ In unreported regressions, I also include interaction terms between socio-demographic characteristics and CCS storage site. The regressions suggest the negative effect of living close to a CCS storage site is stronger for males and for high educated individuals. However, the differences are not statistically significant.

Influence of regional characteristics

I next add, one by one, additional county characteristics as explanatory variables, taking model (1) of table 1 as the baseline regression. The results presented in table 2 show that the significantly negative effect of living in a county with a potential CCS storage site remains robust to the inclusion of additional county characteristics. If anything, the negative effect of CCS storage sites becomes stronger with the inclusion of additional controls. This is a first indication that the negative effect of CCS storage sites is not driven by unobserved county characteristics.

Column (1) adds a dummy for living in the eastern part of Germany to the regression. The result suggests that respondents from the eastern part of Germany have a significantly higher level of acceptance than respondents from the western part of Germany. However, the significantly negative effect of living in a county with a potential CCS storage site remains robust to this inclusion and becomes even stronger compared to the baseline scenario.²⁷ I also find that respondents who live in a county with a high vote share for the Green and Left party show significant lower levels of acceptance (column 2). Both parties strongly oppose CCS.

I also find that respondents who live in a county with coal mining report a significantly lower acceptance of CCS (column 3). Previous experiences with coal mining might reduce the acceptance of further interventions in the ground or might increase fears of further industrialization of the region.

Moreover, I find that respondents who live in a county with high tourism intensity report a significantly lower acceptance of CCS (column 5). Respondents who live in such counties might perceive CCS as a threat to the tourism sector of the region.

In contrast, I do not find a statistically significant effect of CCS power plants (column 4) on the acceptance of CCS. This result seems plausible, as the major risk of CO₂ leakage does not occur when capturing CO₂ but when storing the captured CO₂ in underground formations. I do also not find a statistically significant effect of population density (column 6) on the acceptance of CCS.

Finally, column (7) shows that the CCS storage sites effect remains robust if I control for all regional characteristics at once. The results are very similar if I use the number of CCS storage site rather than the CCS dummy as explanatory variable (see table A-2, column (2), in the appendix).

²⁷ In an unreported additional regression, I also control for living in the city states of Hamburg or Bremen. Again, I continue to find a negative and statistically significant effect of CCS storage sites on acceptance. In addition, I also add a dummy for living in the southern parts of Germany. The negative effect of CCS storage sites on the acceptance of CCS again remains robust

Table 2: OLS regression results equation (II), clustered standard errors

Acceptance	(1)	(2)	(3)	(4)	(5)	(6)	(7)
CCS storage site	-0.2655** (0.1289)	-0.3030** (0.1064)	-0.2608** (0.1224)	-0.2438* (0.1347)	-0.2703** (0.1284)	-0.3200** (0.1259)	-0.2920** (0.1386)
Female	0.3040** (0.1161)	0.3136** (0.1282)	0.3004** (0.1305)	0.3106** (0.1186)	0.3268** (0.1261)	0.3205** (0.1311)	0.2949** (0.1306)
Age	0.0017 (0.0036)	-0.0002 (0.0043)	-0.0003 (0.0041)	0.0013 (0.0036)	0.0001 (0.0043)	-0.0001 (0.0043)	-0.0008 (0.0041)
Education	-0.1022 (0.1010)	-0.1393 (0.1135)	-0.1241 (0.1125)	-0.0962 (0.1005)	-0.1091 (0.1122)	-0.1111 (0.1129)	-0.1382 (0.1131)
Income	0.0004 (0.0005)	0.0002 (0.0005)	0.0002 (0.0005)	0.0003 (0.0004)	0.0001 (0.0005)	0.0001 (0.0005)	0.0002 (0.0005)
East	0.1553* (0.0978)						0.0603 (0.1568)
Green/Left Party		-0.2413** (0.0867)					-0.1751 (0.1124)
Coal Mining			-0.8143*** (0.2192)				-0.7683** (0.2983)
CCS power plant				-0.1303 (0.2362)			-0.1805 (0.2370)
Tourism					-0.0914** (0.0412)		-0.0686 (0.0419)
Population density						-0.0001 (0.0001)	-0.0001 (0.0001)
Constant	2.2857*** (0.2436)	2.7646*** (0.3306)	3.2390*** (0.2944)	2.3508*** (0.2293)	2.5932*** (0.3175)	2.4786*** (0.2864)	3.5991*** (0.3934)
Observations	332	292	292	332	292	292	292
R ²	0.0385	0.0614	0.0597	0.0347	0.0562	0.0437	0.0871

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

Causal pathways

Why does living close to a potential CCS storage site reduces acceptance? One potential answer is that living close to a CCS storage site increases awareness of CCS, and awareness, in turn, decreases the acceptance of CCS (Kniebes et al. 2014 indeed find that higher level of awareness coincide with lower levels of acceptance). A second potential answer is that it reduces the perceived benefits of CCS and/or increases the perceived risks. After all, the risks of storing CCS underground are generally borne by the local population, as the major risk of CCS is CO₂ leakage. In contrast, the overall benefits of mitigating climate change are enjoyed not only by the local but by the general population.

The results in table 3 provide suggestive evidence for the second but not for the first potential explanation. I first add self-reported awareness as a control variable to the baseline regression

(column 1).²⁸ Overall, 84% of the respondents stated to have heard at least somewhat about CCS before the time of the survey. I find that the level of awareness indeed decreases the acceptance of CCS, i.e., respondents with a higher level of knowledge on CCS have a significant lower level of acceptance. However, the effect of living close to a CCS storage site remains largely unaffected. This suggests that the effect does not operate through awareness, as living close to a CCS storage site does not affect awareness. In fact, a regression of awareness on CCS storage site and control variables shows that living close to a CCS storage site has no statistically significant effect on awareness (coefficient of 0.058, p value of 0.464).

Table 3: OLS regression results equation (III), clustered standard errors

Acceptance	(1)	(2)	(3)	(4)
CCS storage site	-0.2470* (0.1397)	-0.1800 (0.1437)	-0.0952 (0.1146)	-0.0992 (0.1197)
Female	0.2511* (0.1296)	0.3055** (0.0982)	0.1176 (0.0867)	0.1489 (0.0889)
Age	0.0024 (0.0037)	-0.0012 (0.0032)	0.0005 (0.0027)	-0.0001 (0.0025)
Education	-0.0509 (0.1040)	-0.0282 (0.0823)	-0.1212 (0.0827)	-0.0780 (0.0816)
Income class	0.0003 (0.0004)	0.0001 (0.0004)	0.0004 (0.0004)	0.0004 (0.0004)
Awareness	-0.1635** (0.0800)			-0.0094 (0.0549)
Risk perception		-0.6054*** (0.0642)		-0.3298*** (0.0669)
Benefit perception			0.7768*** (0.0590)	0.6465*** (0.0685)
Constant	2.5829*** (0.2811)	4.1875*** (0.3155)	0.4358** (0.1844)	1.7395*** (0.3705)
Observations	332	315	320	311
R ²	0.0486	0.2992	0.4986	0.5679

Standard errors clustered at the level of administrative districts in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

I then add an individual's perception of the risk of CCS (column 2), her perception of the benefits of CCS (column 3), and her perception of both risk and benefits (column 4) as control variables. As expected, an individual's level of acceptance decreases in the perceived risk of CCS and increases in the perceived benefits. Importantly, adding perceived risk and benefits halves the coefficient estimate on the CCS storage site dummy and renders the dummy statistically insignificant. This suggests that living close to a CCS storage site reduces acceptance by increasing the perceived risk of

²⁸ I come to broadly similar conclusions if I take equation (II) which includes all regional characteristics, as a baseline regression (see table A-3 in the appendix). The results also hold if I take number of CCS storage sites instead of CCS storage site as an explanatory variable (see table A-2, column 3 and 4 in the appendix).

CCS and decreasing the perceived benefits. In additional regressions, I regress risk perception and benefit perception on CCS storage site and control variables. Somewhat surprisingly, I find that living close to a CCS storage markedly reduces benefit perception (by 0.173 points, p value of 0.068), but increases risk perception only moderately (by 0.079 points, p value of 0.268). This finding is surprising, as especially the risks and not so much the benefits of CCS occur local.

6. Robustness check

The location of CCS storage sites is not random. In fact, potential storage sites cluster in the northwest and the northeast of Germany (see Figure 1, section 3). One might, therefore, be concerned that the dummy for CCS storage sites capture the effect of other unobserved regional characteristics. To deal with this concern, I have already shown that the effect of CCS storage sites is robust to the inclusion of other county characteristics (see table 3, section 5). In this section, I further test whether living close to a CCS storage site also affects the acceptance of solar radiation management (SRM) and afforestation. If so, the observed effect might be caused by a general opposition against climate engineering (CE) technologies in the affected regions.

SRM is a CE technology that counteracts climate change by the injection of sulphate dioxide into the stratosphere. Afforestation of large areas such as the Sahara and the Australian Outback is another CE measure, which is meant to slow down climate change by absorbing CO₂ from the atmosphere. Therefore, all three measures, CCS, SRM and afforestation, are large scale interventions into the earth' climate system to counteract climate change. However, whereas the risks of CCS are confined locally, the risks of SRM and afforestation affect all regions in Germany to the same degree. I would therefore not expect the locations of potential CCS storage sites to affect the acceptance of SRM or afforestation. If they did, this would point towards unobserved factors correlated with both the locations of CCS storage sites and a general opposition against CE technologies.

Table 4 reports the results of re-estimating equation (1) with acceptance of SRM as the dependent variable. The acceptance of SRM and afforestation was elicited in two separate surveys, which were identically structured to the CCS survey. All three surveys were conducted in the same week and respondents were randomly assigned to one of the surveys. Overall, the SRM working data set contains N = 393 observations and the afforestation working data set contains N = 336 observations.

The results in table 4 show that living in a county with a potential CCS storage site has no statistically significant effect on the acceptance of SRM (see columns 1 and 2). In fact, the coefficient estimate of *CCS storage site* is even positive (but not statistically significant). I also do not find any evidence for spill-over effects from living in a county bordering on a county with a CCS storage site on the acceptance of SRM (column 3). In line with these results, I also do neither find a statistically

significant effect of *CCS storage site*, nor of *Number of CCS storage sites*, nor of *CCS storage site neighbourhood* on the acceptance of afforestation (table A-4, appendix). These results support my previous interpretation that the negative effect of CCS storages sites is not driven by unobserved county characteristics.

Table 4: OLS regression results equation (I) for SRM, clustered standard errors

Acceptance	(1)	(2)	(3)
CCS storage site	0.1107 (0.1194)		
Number of CCS storage sites		0.0553 (0.0426)	
CCS storage site neighbourhood			0.0923 (0.1018)
Female	-0.0200 (0.0807)	-0.0185 (0.0814)	-0.0098 (0.0833)
Age	-0.0054 (0.0033)	-0.0054 (0.0033)	-0.0045 (0.0036)
Education	-0.1167 (0.1130)	-0.1096 (0.1126)	-0.0864 (0.1200)
Income	0.0001 (0.0004)	0.0001 (0.0004)	0.0002 (0.0004)
Constant	2.4050*** (0.2440)	2.3994*** (0.2439)	2.2830*** (0.2546)
Observations	393	393	346
R ²	0.0088	0.0121	0.0068

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

7. Discussion and conclusion

This paper has analysed the influence of regional determinants on the acceptance of carbon capture and storage (CCS) in Germany. The CCS technology is able to deliver significant emissions reductions and its deployment both in industrial and power applications is required for reaching the two-degree target (International Energy Agency 2015). However, CCS goes along with several risks. The main risk of CCS, i.e. leakage of CO₂, occurs at the deposits, and affects therefore only regions that have CCS storage sites.

I therefore hypothesize that living close to one of the 408 potential CCS storage sites in Germany reduces the acceptance of CCS, and test this hypothesis using novel survey data. I also shed light on the potential channels through which this ‘not in my backyard’ (NIMBY) effect might operate, and test for the effect of other regional characteristics on the acceptance of CCS in Germany.

My results are as follows: First, I find that living in or next to a county with at least one CCS storage site reduces an individual’s acceptance of CCS significantly. Therefore, the presence of CCS storage

sites appears to reduce the level of acceptance in a relatively large geographic area. These results are in line with previous findings of Krause et al. (2014) who also documents a NIMBY effect for CCS in the US state of Indiana.

Second, I find that the NIMBY effect is robust to the inclusion of other potential determinants of CCS acceptance at both the individual and the regional level. In contrast to Wallquist et al. (2012) but in line with Fischerdick et al. (2008), I find that CCS storage sites but not CCS power plants affect the acceptance of CCS. Moreover, I also find that living in a tourism or coal mining region markedly decreases acceptance. This contrasts with previous findings of Krause et al. (2014) who do not find an effect of coal mining on the acceptance of CCS in the US. However, Krause et al. (2014) do not distinguish between the acceptance of CCS storage sites and CCS power plants. This might be essential though, as the CCS technology is proposed for power plants such as of coal fire plants. Therefore, respondents who live in coal mining regions might gain from the economic benefits of CCS power plants but they might still oppose CCS storage sites in their region.

Third, I present evidence that living close to a CCS storage site reduces acceptance by markedly decreasing the perceived benefits of CCS and also by slightly increasing the perceived risks. This is in line with previous results (Krause et al. 2014; Singelton et al. 2009; Terwel and Daamen 2012). I also show that the effect of CCS storage sites on acceptance does not operate through higher levels of awareness. In contrast to Krause et al. (2014), I find that awareness decreases rather than increases acceptance. However, respondents in my survey report much higher average levels of awareness than those in Krause et al. (2014), so that the two samples might not be directly comparable.

Summing up, my results paint a dark picture of the potential future of CCS storage in Germany. In particular, placing a CCS storage site is likely to meet fierce local resistance. As potential storage sites decrease acceptance not only in their host but also in neighbouring counties, CCS storage sites might stir resistance in a relatively large geographic area. Since the effect operates mainly through the risk and benefit perceptions of local residents, a possible strategy to increase the support of CCS could be to compensate residents for the risks of CCS storage. In particular, residents who live close to a CCS storage site could be compensated for the additional risk they incur by those who are not directly affected. However, paying compensation may also fire back if individuals perceive such payments as proof for the dangers of CCS (Frey and Oberholzer-Gee 1997).

Raising awareness is no promising strategy to win support of residents. Quite to the contrary: awareness seems to decrease rather than increase acceptance (see also Kniebes et al. 2014).

My study lends itself to various extensions. In particular, my study does not focus on the specific risks and benefits of CCS. It would thus be interesting for future research to distinguish between the specific risks and benefits and to analyse the effect of compensating local residents. Moreover,

future research could also explicitly focus on Bio-energy with carbon capture and storage (BECCS), as it has been shown for climate engineering that describing technologies with natural processes increases acceptance (Corner and Pidgeon 2014).

8. References

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9. Appendix

Table A-1: Summary statistics

Variables	Domain	CCS		SRM		Afforestation	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Acceptance	1 - 4	2.5421	0.9105	2.1119	0.9355	3.130	0.7044
Female	0 - 1	0.4638	0.4994	0.4936	0.5005	0.4791	0.5003
Age	18 - 91	49	14.0685	51	14.6314	48	14.3705
Higher education	0 - 1	0.3042	0.4607	0.3180	0.4663	0.3095	0.4629
Income	125 - 7500	1676.20	115.246	2497.13	147.51	1571.42	107.97
Awareness	1 - 3	1.7530	0.7203	1.2620	0.4948	1.7023	0.6872
Risk perception	1 - 4	2.8730	0.7917	3.2826	0.7739	2.4357	0.7532
Benefit perception	1 - 4	2.5562	0.8209	2.4582	0.7817	2.9656	0.7398
N		332		393		336	

Summary statistics are based on the observations that are used in the baseline regression (equation I)

Table A-2: OLS regression results equation (III) with equation (II) as a baseline scenario, clustered standard errors

Acceptance	(1)	(2)	(3)	(4)
Number of CCS storage sites	-0.1082*** (0.0264)	-0.1029*** (0.0273)	-0.0548** (0.0241)	-0.0594** (0.0269)
Female	0.3166** (0.1137)	0.2997** (0.1282)	0.1564* (0.0883)	0.1376 (0.0929)
Age	0.0011 (0.0037)	-0.0010 (0.0042)	-0.0001 (0.0025)	-0.0002 (0.0028)
Education	-0.1118 (0.1040)	-0.1524 (0.1161)	-0.0847 (0.0832)	-0.0577 (0.0842)
Income	0.0004 (0.0004)	0.0003 (0.0005)	0.0004 (0.0004)	0.0004 (0.0005)
East		0.0401 (0.1443)		0.1250 (0.1532)
Green/Left Party		-0.1547 (0.1129)		0.0282 (0.0909)
Coal Mining		-0.7783** (0.3011)		-0.7693** (0.3750)
CCS power plant		-0.1719 (0.2347)		-0.1273 (0.1748)
Tourism		-0.06750 (0.0450)		-0.0664* (0.0359)
Population density		-0.0001 (0.0001)		-0.0001 (0.0001)
Awareness			-0.0108 (0.0559)	-0.0258 (0.0628)
Risk Perception			-0.3300*** (0.0673)	-0.3024*** (0.0699)
Benefit Perception			0.6423*** (0.0679)	0.6693*** (0.0715)
Constant	2.3433*** (0.2290)	3.5718*** (0.3866)	1.7476*** (0.3728)	2.4846*** (0.6352)
Observations	332	292	311	275
R ²	0.0422	0.0909	0.5703	0.6046

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

Table A-3: OLS regression results equation (III) with equation (II) as a baseline scenario, clustered standard errors

Acceptance	(1)	(2)
CCS storage sites	-0.2920** (0.1386)	-0.1794 (0.1309)
Female	0.2949** (0.1306)	0.1347 (0.0933)
Age	-0.0008 (0.0041)	-0.0001 (0.0028)
Education	-0.1382 (0.1131)	-0.0507 (0.0831)
Income	0.0002 (0.0005)	0.0004 (0.0005)
East	0.0603 (0.1568)	0.1446 (0.1494)
Green/Left Party	-0.1771 (0.1124)	0.0202 (0.0871)
Coal Mining	-0.7683** (0.2983)	-0.7627** (0.3749)
CCS power plant	-0.1805 (0.2370)	-0.1347 (0.1804)
Tourism	-0.0686 (0.0419)	-0.0669** (0.0335)
Population density	-0.0001 (0.0001)	-0.0001 (0.0001)
Awareness		-0.0266 (0.0613)
Risk Perception		-0.3016*** (0.0696)
Benefit Perception		0.6720*** (0.0722)
Constant	3.5991*** (0.3934)	2.4876*** (0.6357)
Observations	292	275
R ²	0.0871	0.6041

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

Table A-4: OLS regression equation (1) for afforestation, clustered standard errors

Acceptance	(1)	(2)	(3)
CCS storage site	-0.0688 (0.1724)		
Number of CCS storage sites		-0.0076 (0.0479)	
CCS storage site neighbourhood			0.0256 (0.0920)
Female	-0.0916 (0.0720)	-0.0907 (0.0727)	-0.0681 (0.0739)
Age	0.0058** (0.0026)	0.0057** (0.0026)	0.0063** (0.0027)
Education	-0.0419 (0.0817)	-0.0438 (0.0813)	-0.0918 (0.0816)
Income	0.0004 (0.0003)	0.0003 (0.0003)	0.0004 (0.0003)
Constant	2.8480*** (0.1723)	2.8493*** (0.1716)	2.8186*** (0.1717)
Observations	336	336	301
R ²	0.0297	0.0289	0.0358

Standard errors clustered at the level of administrative districts in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Acceptance is measured on a scale of 1 (strongly disagree) to 4 (strongly agree).

Information provided in the CCS video

Sunlight warms the Earth and its atmosphere. Greenhouse gases in the atmosphere such as CO₂ ensure that some warmth remains close to the Earth's surface. This makes the Earth warm enough for humans, animals, and plants to live on.

Since the start of industrialisation around 1850, people have emitted a great amount of greenhouse gases by burning coal, oil, and gas. These gases trap more heat in the atmosphere and cause a gradual increase in the average global temperature.

Since 1900, the global temperature has risen by approximately 0.8°C. Almost all countries agree that the increase in the average global temperature should not exceed 2°C compared to pre-industrial levels. This is called the 2°C target.

By 2100, a further increase in temperature between 0.9 and 5.4°C is expected. The development depends strongly on the amount of greenhouse gases emitted in the future. To reach the 2°C target, the current level of emissions would have to be cut by more than half until 2050. By 2100, greenhouse gas emissions would have to be reduced to almost zero.

It is virtually certain that climate change will cause a rise in sea levels. The frequency of heat waves is very likely to increase as well as the number of heavy precipitation events in many regions. It is likely that in the future, more areas will be affected by longer droughts and that the frequency and intensity of tropical cyclones will increase. In addition, part of the emitted CO₂ is absorbed by the ocean, causing ocean acidification.

There are different ways to deal with climate change:

We can reduce greenhouse gas emissions or adapt to the new climate by building dikes. Another option is carbon capture and storage sub-seabed (CCS).

The CCS technology captures CO₂ from the industrial combustion of fossil fuels. The CO₂ is compressed and stored in suitable geological formations under the seabed. It is not released into the atmosphere. This process additionally uses approximately 25% of the generated energy, which increases the overall demand for fossil fuels.

On a small scale, CO₂ has already been stored in the ground for approximately 30 years. CO₂ is injected for the recovery of oil and gas to make this process easier. The experiences indicate a high level of storage safety.

Former oil and gas fields as well as sub-seabed saline aquifers are considered to be safe and permanently suitable deposits.

Pipelines and ships carry the compressed CO₂ to the deposits.

There, it is pumped into tiny hollows of the sub-seabed deposit, where it has to be stored for several thousands of years. During this time it merges with the rock and it is rendered permanently harmless.

Scientists think further applied research on CCS would be useful. The processes, benefits and risks are already well understood.

Some expected benefits and risks of CCS are now introduced to you.

Benefits of CCS are that global warming as well as acidification of the oceans would be slowed down. Furthermore, deploying CCS would be less expensive than an energy transition from fossil fuels to renewable energies.

The risks of CCS include the possible leakage of CO₂ from the well or from the deposits caused by increased pressure. This could lead to a local acidification, which would endanger the biodiversity of that area.

Conclusion

This dissertation explores public perception of new climate change mitigation technologies in Germany. New climate change mitigation technologies encompass two approaches, climate engineering (CE) and carbon capture and storage (CCS). In this dissertation, I focus on two specific CE measures, namely solar radiation management via stratospheric sulphate injection (SRM) and afforestation, as well as on CCS. All three measures aim to counteract climate change by large scale interventions into the earth's climate system but differ with respect to their side effects, effectiveness, cost effectiveness, and their degree of development. Projections by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) suggest that CE and CCS might both be crucial for limiting global warming to a 2°C increase (IPCC 2014; IEA 2015).

New climate change mitigation technologies are controversially discussed by academics, representatives from the business community, non-governmental organizations (NGOs), and governments, but have received only little attention by the broader public. Nevertheless, public perception might crucially determine whether CE and CCS become part of an integrated response for a climate change risk management strategy (Rickels et al. 2011). Adverse public perception of CE and CCS measures might well impede their further development and might hinder their large-scale application in practice. Past experience shows that even small-scale field research on CE and CCS often faces widespread public protests, and that such protests might well bring research projects to an immediate halt. For instance, public protests stopped the exploration of CCS test fields in Germany and hindered CE field tests in the UK. However, such tests, involving both laboratory and field research, are required to credibly assess the technical feasibility and risks of CE and CCS technologies, and hence to make them deployable on a large scale (Rickels et al. 2011; Rayner et al. 2009). Therefore, public approval of new technologies to mitigate climate change is necessary if those technologies should become a viable option to counteract climate change in the future. The future challenges of these technologies are thus as much political and social as they are technical (Royal Society 2009).

So far, the social impact of most new climate change mitigation technologies has not yet been adequately evaluated. In particular, there is little evidence on the public perception of CCS and even less evidence on the perception of CE technologies (Macnaghten and Szerszynski 2013). However, thorough knowledge on the public perception of these technologies might be a prerequisite for starting a public engagement process, which, in turn, seems necessary to ensure acceptance of future research in the field. In fact, the Oxford Principles, a set of guiding principles for the governance of climate engineering research agreed upon by experts, call explicitly for public

participation and democratic involvement in climate engineering decision-making (Rayner et al. 2009).

Against this background, the aim of this dissertation is to provide empirical evidence on the public perception of SRM, CCS, and afforestation in Germany. This evidence is based on novel online survey data on respondents aged 18 or above, which I elicited between 2012 and 2014. To ensure (internet) representativeness, respondents were sampled using quotas for the characteristics of gender, age, and state of residence.

Based on this novel data, the three main objectives of the dissertation's five research papers are as follow:

1. To investigate factors that drive the public perception of CE and CCS technologies, and compare the perception of individuals who are well informed about a technology with those who are less well informed.
2. To explore how public perception changes over time, and is influenced by transient emotions.
3. To contribute to methodological questions on how the willingness to pay for the avoidance or deployment of a CE technology can be elicited.

With respect to the first research objective, I find that the public perception of SRM, CCS, and afforestation differs strongly. Respondents are generally highly sceptical of CCS and SRM, and prefer afforestation over both CCS and SRM. Receiving additional information on the technologies reduces the acceptance of each technology but leaves the ranking of the three technologies intact. I also find that respondents are more willing to accept laboratory than field research on SRM, and that regional factors affect individuals' acceptance of CCS. In particular, respondents who live close to a potential CCS storage site reveal significantly lower acceptance rates of CCS than those who do not. These results suggest that placing a CCS storage site is likely to meet fierce local resistance.

With respect to the second research objective, I find that in repeated surveys the acceptance of SRM typically increases over time and that the increase becomes larger with the time duration between two surveys. Informing lay people about SRM initially provokes strong emotions. These emotions then cool off over time and acceptance increases as a result. In addition, other individual specific factors, such as cognitive reflection and impatience, also affect the change in acceptance.

With respect to the third research objective, my key finding is that the newly developed Range-WTP method, which explicitly allows for preference uncertainty, is better suited to elicit the WTP for the avoidance of SRM than the traditional, widely used Point-WTP method. The Range-WTP outperforms the Point-WTP method both in terms of theoretical validity and test-retest reliability.

Summing up, this dissertation uses novel survey data to shed light on different aspects of the public perception of new climate change mitigation technologies in Germany. The aim of studying public perception and its determinants is not to enforce acceptance or to educate the broader public but rather to take public concerns into account before decisions on these technologies are made (Pidgeon et al. 2013). Knowledge about public perception of new technologies to mitigate climate change is essential to make informed decisions about further research and for developing a possible portfolio of mitigation technologies (Carr et al. 2013; Rayner et al. 2009).

My dissertation suggests that public opinion on new climate change mitigation technologies might change significantly over time. In particular, acceptance might decrease with additional knowledge (Paper III) or it may increase as respondents' transient emotions cool off over time (Paper IV). It is therefore important to regularly up-date our information on the public perception of climate change mitigation measures. Such information can then form the starting point for a broad process of dialogue and knowledge exchange (Royal Society 2011). The widespread skepticism against CCS and SRM in Germany shows that such dialogue is urgently needed if these technologies should have a future as important options to limit global warming. In addition, the public perception of alternative scenarios also requires research and public discussion. After all, missing the 2°C target becomes increasingly likely according to current projections if adverse public opinions prevent the implementation of CE and CCS technologies.

Future research might build productively on my work, addressing caveats of my analyses. In particular, my quantitative analyses of survey data are — as all analyses of survey data — subject to limitations, and can only provide an incomplete snapshot of public opinions. Survey respondents can, for instance, only choose among pre-specified options. Moreover, my data set is only internet representative. Therefore, qualitative studies and quantitative studies analysing probability-based general population samples might complement and add to my work.

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Eidesstattliche Erklärung

Ich erkläre hiermit, dass ich meine Doktorarbeit 'Essays on the economics of new technologies to mitigate climate change' selbstständig und ohne fremde Hilfe angefertigt habe und dass ich als Koautor maßgeblich zu den weiteren Fachartikeln beigetragen habe. Alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen der aufgeführten Beiträge wurden besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert.

Kiel, den 18. April 2016

Carola Braun