The Role of Health Co-Benefits in Assessing Climate Mitigation Costs.

Increasing Ambition to Act on Climate Change.

In collaboration with NewClimate Institute

Marcel Koßmann

6207596

m.p.kossmann@students.uu.nl

Faculty of Geosciences

Sustainable Development – Energy & Materials

Supervisor Dr. Robert Harmsen

Second reader: Dr. Wina Crijns-Graus

Master Thesis
(45 EC)

NEW CLIMATE INSTITUTE

Universiteit Utrecht

Abstract

Increasing the action to act on climate change and increasing the ambitions to do so, is an important issue in current policy debates. Governments are lacking behind their climate goals and it becomes difficult to achieve a 1.5˚C pathway by the end of the century (Climate Action Tracker, 2019; IPCC, 2018a). In this thesis, an indicator was analyzed which could incentivize policymakers to increase their climate mitigation ambition. This thesis identified the emission levels at net-zero economic costs when including health co-benefits from reduced air pollution for China and India in 2030. The indicator was further used to determine reductions in the total abatement costs coming from health co-benefits. The analysis is based on an extensive data collection of co-benefit values and emission trajectories with consistent mitigation cost estimates from two different integrated assessment models IMAGE and POLES. To identify the emission levels at net-zero costs for a 1.5˚C pathway in 2030, the monetized co-benefits were implemented in a Marginal Abatement Cost Curve.

The identified emission level ranges from 2.9 to 7.2 GtCO_2 for China and from 0.7 to 1.3 GtCO_2 for India. The results illustrate the number of emissions that can be achieved at net-zero cost when accounting for health co-benefits from reduced air pollution. For both countries, these emission levels make up over 50% of the total emissions gap in 2030. Illustrating these emission levels besides the reductions of total mitigation costs is an additional dimension to incentivize and inform governments.

Limitations in data characteristics on cost estimates for co-benefits and IAMs for 2030 reduced the persuasiveness of the results. Using co-benefits as an additional dimension to assess the effects of implementing local mitigation measures could increase the useability of the indicator. Using measure specific cost estimates could further increase the usefulness of the indicator for advising policymakers. Yet, the results show for both countries the significant effect just the inclusion of health co-benefits can have on the required mitigation costs. Climate change demands action and co-benefits can incentivize that.

Key concepts:

co-benefits, climate mitigation costs, emission pathways, net-zero costs, integrated assessment models

Table of Contents

List of Figures

1 Introduction

1.1 Background

In December 2015 a historic agreement was reached in Paris, France at the 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) to act against climate change (UNFCCC, 2018). The nations agreed on the aim of "*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" (UNFCCC, 2015, Article 2).

Prior to COP21, 192 of the 197 parties to the UNFCCC submitted their intended nationally determined contributions (INDCs) which represented about 98% of global emissions in 2012. These INDCs became an integral part of the agreement and built its foundation. To date, 170 countries ratified their INDC, translating them into nationally determined contributions (NDCs) (den Elzen et al., 2019). The NDCs contain the countries national targets and their means to achieve these targets (UNFCCC, 2018).

Keeping global warming below 1.5°C would require a reduction in global emissions by 50 percent by 2030 (IPCC, 2018b). About 75% of the current climate pledges by countries are partially or fully insufficient to reach this reduction by 2030 (Watson et al., 2019). Even if the current NDCs would be fully implemented, their aggregated emission reduction would not be enough to keep the global warming even below the 2°C goal of the Paris Agreement (Rogelj et al., 2016). Recent analysis shows further, that the carbon budget for the 2°C target would already be exhausted close to 2030 under current NDCs, illustrating the need to increase short-term ambition and climate action (Bertram et al., 2019). Many major economies are set to miss their NDC targets in 2020 and 2030 reducing the probability to keep the overall commitments of the Paris Agreement by the end of the century (Climate Analytics et al., 2018). It is, however, important to note, that these NDCs are not set in stone, but are flexible and can still be adapted to further increase efforts required to meet the Paris targets (den Elzen et al., 2019).

The scientific consensus on the negative implications of a further increase in emissions is clear and over 11.000 scientists recently signed another warning statement for policymakers (Ripple et al., 2019). Besides most scientists in related fields, the public also increasingly demands higher ambition by governments to act on climate change with predominantly young people leading the global mobilization (Watson et al., 2019).

One major reason for the world's slow action against climate change is the high short-term investment needs. Many greenhouse gas (GHG) mitigation options require significant upfront investments while yielding their benefits only far in the future. The benefits for the investment are also not necessarily received by the individuals investing, but rather by all and especially those directly affected by climate change. This could result in climate mitigation being postponed or considered the duty of others (Wagner et al., 2012). The cost of mitigation is felt domestically, while the benefits accrue globally, creating a global "free-rider" problem (Sobhani, 2018).

But even before the Paris Agreement, estimates forecasted increasing mitigation costs for delayed climate action (Rogelj et al., 2013). The costs are therefore only going to increase the more climate mitigation is postponed. Additionally, some countries may have more means to pay these significant costs than others due to their economic power. It is estimated that the impacts of climate change will affect the poor regions of the earth significantly more than the rich (Mendelsohn et al., 2006; WHO, 2009).

However, the economics of climate change mitigation is often discussed based on a narrow definition of climate mitigation costs (Wagner et al., 2012). Many integrated assessment models (IAMs) or other economic models, used for climate policy decisions, maybe grossly overestimating the cost of climate mitigation (Stern, 2016) especially in comparison with the cost of non-action (The Economist, 2019). One major reason for this is, that co-benefits of climate policy are not included in IAMs (Hare et al., 2018). Following the definition of the IPCC, co-benefits are defined as positive unintended side effects of governmental policy (IPCC, 2014a, Box 3.4).

1.1.1 Synergies and Trade-offs of SDGs and Climate Policy

The latest special report on the impacts of 1.5°C warming by the IPCC synthesized the synergies and trade-offs between mitigation options and sustainable development. The report concludes that an understanding of these positive and negative interactions can increase public acceptance, foster faster action as well as support the design of equitable mitigation options that protect human rights (IPCC, 2018b).

Figure 1 shows the synergies and trade-offs from three mitigation categories, namely energy demand, energy supply, and land & ocean mitigation options (IPCC, 2018b). Especially energy demand options have synergies with almost all sustainable development goals with all of them also exceeding the trade-offs under high robustness and agreement. Resource and energy savings, for instance, have synergies with sustainable production and consumption (SDG 12), access to energy (SDG 7), innovation and infrastructure development (SDG 9) and sustainable city development (SDG 11). While energy supply options do not have a broad distribution of synergies across all SDGs like energy demand options do, but instead the synergies are enforced in fewer SDGs like clean water infrastructure (SDG 6), access to energy (SDG 7), responsible consumption (SDG 12) as well as life and land (SDG 15). The three wheels on the bottom of the graphic show the tradeoffs between the mitigation options and the SDGs. It is, however, important to note that in all the three mitigation categories the synergies always exceed the tradeoffs. However, for energy supply options some tradeoffs especially with SDG 6 clean water, are strong. These are for instance described as the negative environmental effects of nuclear energy when replacing fossil fuels, for instance on water use (IPCC, 2018b).

The report illustrated the additional benefits policies can have, not only on the main objective they are targeting but also on other additional objectives they could impact. It is important for policymakers to recognize these interlinkages as it is in their interest to meet as many SDGs as possible.

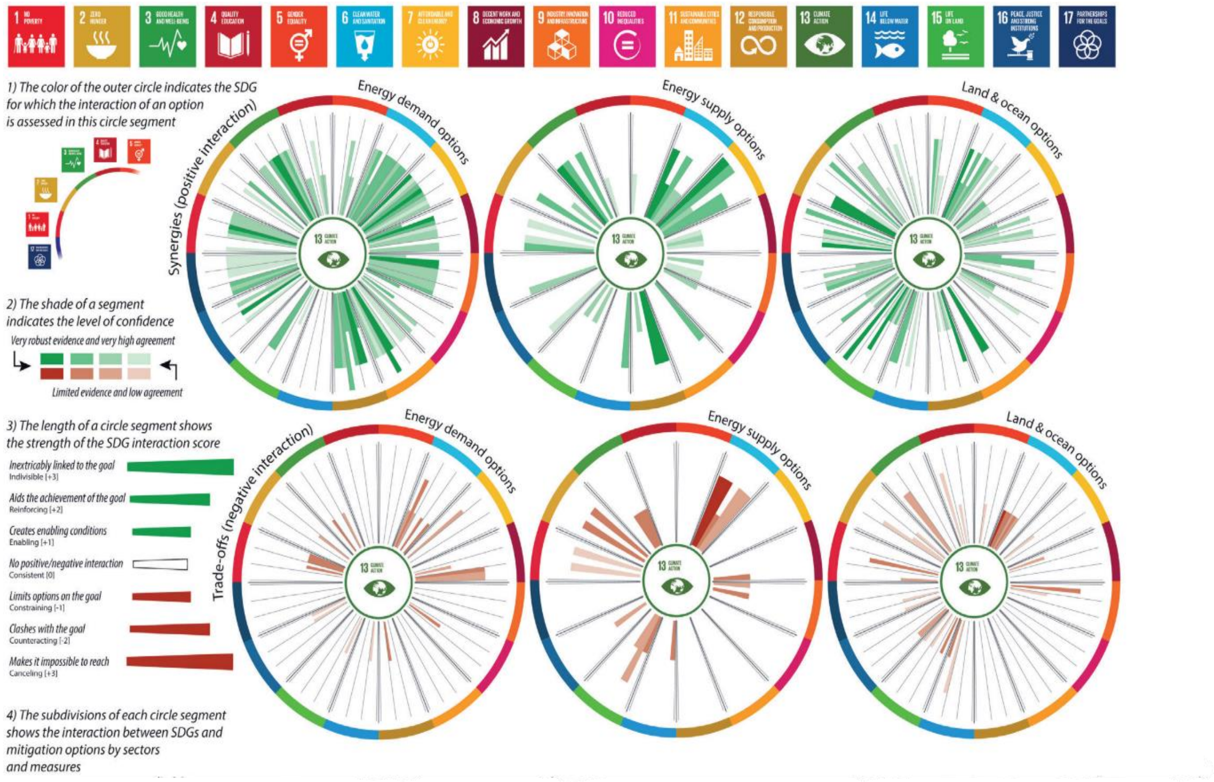

Figure 1: Synergies and trade-offs between mitigation options and Sustainable Development Goals (SDGs) (IPCC, 2018a)

In the context of climate mitigation objectives and not specifically SDGs, these interlinkages between different policy objectives are described as co-impacts. Examples of positive co-impacts, or co-benefits, are reduced air pollution, increased energy security or positive employment effects. The IPCC emphasizes especially in their latest reports the role these co-benefits could have for driving down the mitigation costs (IPCC, 2018b). With some studies indicating that climate policy costs are overstated when co-benefits are neglected (Östblom and Samakovlis, 2007). The IPCC mentions multiple such co-benefits in their Fifth Assessment Report (AR5) (IPCC, 2014a).

1.1.2 Consideration of Co-Benefits into Climate Change Policymaking

For many years already the extent of positive side effects of climate policy is acknowledged in the literature (Mayrhofer and Gupta, 2016). Some authors, therefore, questioned, whether creating policies not only with reducing emissions in mind but also emphasizing multiple other benefits could strengthen climate policy and increase ambition and action in the short term. One of those well-known studies was conducted by Nemet et al. in 2010 who criticized the use of co-benefits to improve climate policymaking.

In theory, co-benefits could illustrate the immediate and local benefits through, for instance, reduced air pollution or increase crop yields relatively contemporary to the mitigation effort. This is in contrast to pure climate benefits, whose negative impacts and the positive implications of avoiding them, are located far in the future (Nemet et al., 2010). Emphasizing the immediate and local benefits of climate mitigation could, therefore, increase public support and political will for enacting climate policy (Sobhani, 2018). Co-benefits could engage more actors, which are averse to the cost of climate action or unmotivated by the avoided climate damages (Nemet et al., 2010). While Nemet et al. agrees, that co-benefits could be an important issue in framing climate policies, they argue that the barriers and uncertainties around co-benefits are the reason, that they so far were not able to be implemented in climate policy and will continue so until the valuation of co-benefits has improved. Nemet et al. further argues that the improvement of valuation of just a single co-benefit does not help to increase the stringency of climate policy in total, but that a whole assessment is required of all co-benefits and their interlinkages in risk characteristics, driving forces and spatial scales (Nemet et al., 2010).

Especially in countries like China or India, the negative impacts of fossil energy use are visible and increasing as recent news further illustrates (The Washington Post, 2019). Where the negative impacts of avoided climate mitigation are widespread, the governments would want to attempt to relieve the whole country of these negative implications and not only local communities. Relieving local communities of already one major climate damage like heavy air pollution is something countries would pursue. Countries like China and India could, therefore, tackle multiple issues with integrated policies at once. Including co-benefits in this approach could furthermore illustrate that the real costs for the required measure packages would be lower than they seem (McCollum et al., 2013).

Since Nemet et al.'s study in 2010, climate policy discourse has changed. Nemet et al. argued in 2010, that the "*climate policy discourse [will] continue as one of cost minimization*" (Nemet et al., 2010, p.6). While the focus on minimizing cost continues today, other dimensions have been added to that context since 2010. With the introduction of the Sustainable Development Goals in 2015, the context of climate action was expanded to encompass multiple dimensions of SDGs (United Nations, 2019). While the Millennium Development Goals (MDGs) were generally only focusing on development, the new SDGs are specifically referring to "sustainable development" including multiple goals linked to climate policy (IPCC, 2018a). Countries now also strive towards accomplishing multiple sustainable development goals with their policies (United Nations, 2019).

With the Paris climate conference in 2015, the perception of climate change and climate action changed with many countries increasing their ambitions, with one commentary even describing the conference as a "game-changer" in the climate policy discourse (Kinley, 2017). With the conference, there was also a shift in perception of who has to take action. Compared to the Copenhagen pledges, the Paris Climate Conference abandoned the distinction of Annex I and Annex II countries, emphasizing that every country has to take action as opposed to just the Annex I countries as it has been the case before (Bodansky, 2015). And as many studies are illustrating, especially those Annex II countries are the countries that could benefit the most from co-benefits (Markandya et al., 2018; Vandyck et al., 2018; West et al., 2012).

Due to the changes in perception, the focus on assessing only a single co-benefit like health can already be enough to stimulate governmental action. Averchenkova et al. for instance sees for China a "*recent shift away from sole emphasis on economic growth to greater attention to air quality and climate change [that] has led to increased investment in renewable energy sources and strengthened environmental policies and laws*" and therefore clearly mentioning co-benefits as the reason for governmental action (Averchenkova et al., 2016,p.9).

In contrast to what the study by Nemet et al. suggested, the inclusion of co-benefits into climate policymaking makes more sense now than it did in 2010. Countries are now actively looking to meet multiple sustainable development objectives. Since Paris, the need for higher ambition by not only the developed but also the developing countries was emphasized and especially for those countries' co-benefits could be immense. Even though uncertainties and limitations surrounding co-benefits still persist today, their importance increased, making the consideration of them for climate policymaking much more logical than in 2010.

1.2 Gaps in Knowledge

Many peer-reviewed studies model certain benefits to be higher than the required mitigation costs mainly for developing regions but also for developed countries (Vandyck et al., 2018) and for certain regions also for a 1.5°C scenario (Markandya et al., 2018). In recent years many influential bodies like for instance IRENA, are calling for adequately including co-benefits into energy markets since their monetary evaluation could offset the mitigation costs often by a significant degree (IRENA, 2016). However, the literature of peer-reviewed papers or grey literature which reflects this call is limited.

Vandyck et al. compared specific mitigation costs to specific co-benefits resulting from reduced air pollution, both in $/t$CO_2$ for major economies showing that the benefits can be higher than the costs for some regions (Vandyck et al., 2018). Markandya et al. compared total cumulative costs for major emitters when including health co-benefits approving the results by Vandyck et al. (Markandya et al., 2018).

Ürge-Vorsatz reviewed the cost-benefit ratios for selected mitigation measures including health co-benefits opposed to the previous studies who applied the co-benefits to the full economy without knowledge on specific measures. The paper concluded that even for some specific measures the benefits are higher than the costs (Ürge-Vorsatz et al., 2014). Fekete et al. quantified the emission reduction potential per country for mitigation actions with co-benefits but did not monetize them (Fekete et al., 2013). A background paper for the recent "New Climate Economy" report calculated the additional mitigation when including four different co-benefit types in a marginal abatement cost curve (MACC) on a global level. The co-benefits used were however highly aggregated (The New Climate Economy, 2015).

Only one study was found, that transferred the monetized co-benefit back into a specific emission reduction level at net-zero costs while accounting for co-benefits. In contrast to the study from Ürge-Vorsatz (2014), the authors in this study did not only assess the cost-benefit ratios of measures in one of their approaches but also used these ratios to calculate specific emission reduction potentials, while Ürge-Vorsatz did not. The paper by Alexander et al. (2015) quantified the cost-effectiveness of different measures when including monetized health benefits from reduced air pollution. The authors identified an additional mitigation potential of 4.6 – 7.8 GtCO_2 in 2030 without imposing any additional economic burden on those undertaking the efforts (Alexander et al., 2015).

The analysis of Alexander et al. focused solely on one type of co-benefit, health benefits. Further, the analysis was conducted using aggregated data on a global level, while drawing country-specific conclusions from it. The paper by Alexander therefore still leaves some important questions open. It leaves open how the results would change for using country-specific co-benefit data and if that would make the result more impactful. The paper did the analysis solely for the REMIND model developed by the Potsdam Institute of Climate Impact Research (PIK). Doing a comparing analysis between multiple IAMs would show how the choice of the integrated assessment model influences the results. Further, the analysis by Alexander et al. is now almost 5 years old and is using data from even earlier. Since then, the context of climate action and especially the perception of climate change has come much more into focus with now a growing part of the population calling for increasing ambitions.

1.3 Research objective and research question

Governments are lacking behind the necessary climate efforts for reaching a 1.5˚C pathway as recommended by the IPCC (IPCC, 2018a). Governments need to increase their ambitions to act on climate change the next years to avoid major climate effects in the second half of the decade.

The main objective of this thesis is to create an indicator that can be used to increase ambitions. For this, the emission level, possible at no additional economic costs, when accounting for health-related co-benefits for China and India in 2030 was chosen. In countries, where air pollution is a major issue, health benefits from reduced air pollution could be among the largest co-benefits and illustrate the biggest potential reduction of costs. Showing this potential in terms of the share of closing the mitigation gap between the reference and the mitigation pathway could help governments that the target may be closer than they think and in turn, could increase ambition.

It was investigated whether this net-zero emission level could potentially be used to increase ambition on climate mitigation efforts. To determine this indicator a method was developed using openly accessible data on health co-benefits and emission and mitigation cost data from an integrated assessment model database. The results of this thesis have been compared with the results from Alexander et al. (2015) while applying a different method, including a wider literature base on the health co-benefits as well as using openly available emission and mitigation cost estimates for two different integrated assessment models.

The main research question aimed to answer the research objective of this thesis is as follows:

What is the additional country-specific emission level at net-zero costs considering health co-benefits in 2030 for China and India?

To show the effect that already one well-recognized co-benefit could have on the mitigation costs, monetized co-benefit values, found in literature, have been aggregated, sorted and partially adapted to display the monetized benefit over the number of emissions avoided for two major economies in 2030 in section 3.1. In a second step, the emission and cost data provided by the ADVANCE project database for a 1.5°C scenario for the two IAMs IMAGE and POLES have been used to estimate a marginal abatement cost curve in 2030 in section 3.2. When including the in the first step estimated health co-benefit values with the in the second step estimated MACC, a third shifted marginal abatement cost curve was drafted (section 3.3). Using this curve, the emission level at net-zero costs was calculated in section 3.4 and 3.4.1.

1.4 Collaboration with NewClimate Institute

This thesis is conducted in collaboration with NewClimate Institute in Cologne. While parts of the thesis will be used as theoretical input and orientation on further projects from NewClimate, the contents and outputs of this thesis are my own. NewClimate Institute acted primarily in an advisory role. Writings and thoughts that are not my own are indicated as such.

2 Theoretical Framework and Key Concepts

The research is based on several key concepts illustrated in the theoretical framework below. Climate Policy describes policies generally aimed to reduce CO_2 and limited global warming. Integrated assessment models (IAM) are used to inform policymakers, for instance, about the impact of certain policies on the possible amount of mitigation and the mitigation costs associated with that. The cost estimation of IAMs however usually does not include additional externalities achieved by a reduction of CO_2 which could have an impact on the total mitigation costs. For the cost estimation, IAMs apply Marginal Abatement Cost Curves (MACC). Co-impacts can partially be monetized. Including the monetized co-impacts into the MACC could lead to a change in the estimated mitigation costs and give policymakers a more complete picture for drafting their policy.

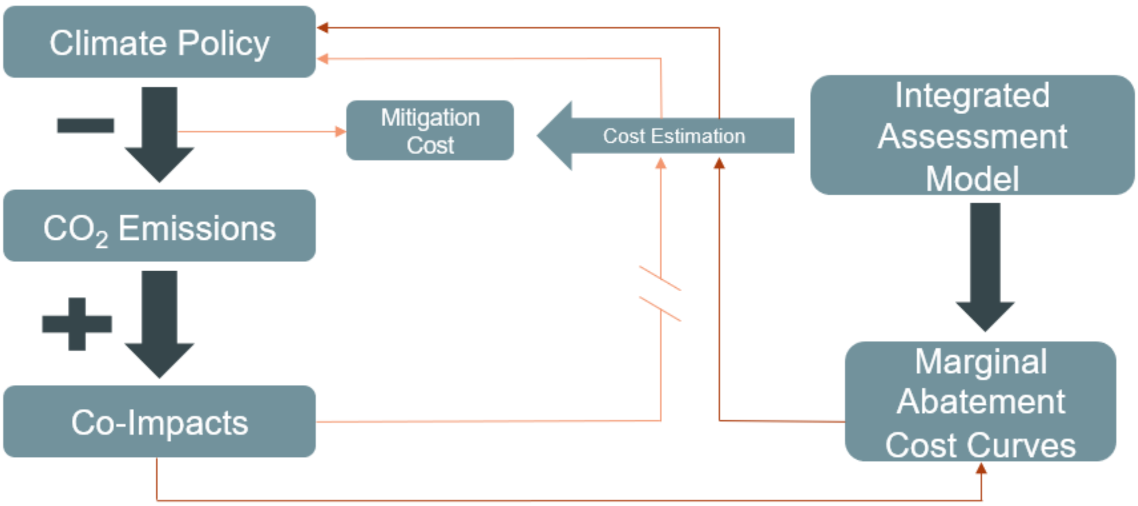

Figure 2: Theoretical framework illustrating the relation of the key concepts of this study

The following section defines the individual key concepts in more detail and illustrates the relation between them as a base for the applied method.

2.1 Co-Impacts

The Intergovernmental Panel on Climate Change's (IPCC's) fifth assessment report synthesized the positive and negative side-effects of climate mitigation policy and technologies under the term "co-impacts" (IPCC, 2014a). For both the positive (co-benefits) as well as the negative side-effects (adverse side-effects) many different terminologies exist.

The IPCC gives multiple examples of a range of different co-impacts of different mitigation measures per sector (IPCC, 2014a). Each Sector has different examples of mitigation options. The co-impacts itself are categorized into economic, social and environmental co-impacts. The authors furthermore give uncertainty indices in the form of the base of evidence and the agreement under peer researchers for each co-impact (IPCC, 2014a).

Especially the transport and building sectors have in all of the co-benefit categories a clear majority of synergies over trade-offs. The economic categories show profoundly the synergies of increased energy security for all mitigation measures for both transport and buildings. The social category is characterized mainly by health benefits coming from reduced air pollutants, but also include increased productivity for workers due to more efficient utilities in the building sector or reduced travel-time in transport. The environmental synergies are mainly categorized as reduced resource use and reduced impact on biodiversity.

The same key synergies can also be found for the sector of energy supply; however, most mitigation options are also accompanied by trade-offs. This is, for instance, the case for using fossil fuels including Carbon Capture and Storage (CCS) as a substitute for coal which has almost solely trade-offs. Especially the co-benefit of health from reduced air pollutants is seen by the researcher as highly impactful as the IPCC sees robust evidence supporting it available in the literature.

Co-impacts of a certain policy or technology-based mitigation strategy can follow different pathways. Each pathway can result in one or multiple co-impact endpoints. As an example of how climate mitigation can result in different co-impacts, Ürge-Vorsatz et al. (2014) developed a schematic overview shown in Figure 3 below. Climate mitigation measures, for instance, like a fuel switch not only reduce the CO_2 emissions but also affect other, more local externalities. These impacts can either be positive or negative. Since many air pollutants are co-pollutants of CO_2 emissions, a reduction of the latter also results in a reduction of other air particles. This reduction has many co-impacts like changes in the provision of ecosystem services, changes in crop yields and changes in mortality and morbidity. These endpoints furthermore have feedback loops to other co-impacts like employment, energy security or social benefits like comfort effects (Ürge-Vorsatz et al., 2014).

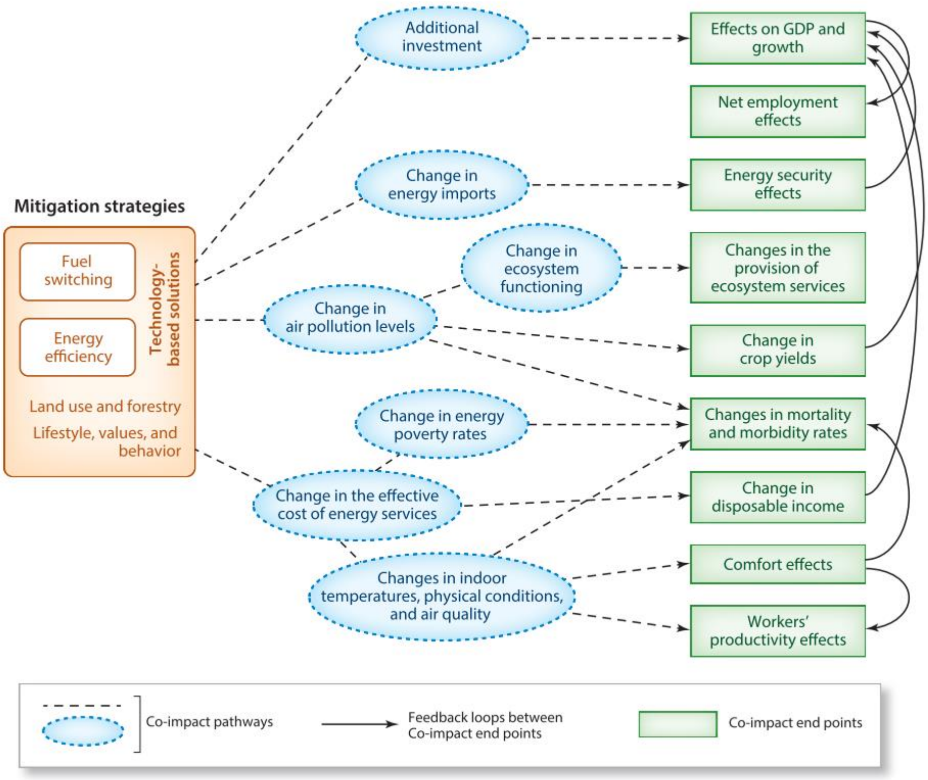

Figure 3: Conceptualization of welfare effects resulting from technology-based climate mitigation strategies (Ürge-Vorsatz et al., 2014)

2.1.1 Co-Benefits

The term “co-benefits” already appeared in academic literature around 1991 and gained more traction after the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (AR3) (Mayrhofer and Gupta, 2016). There is however no definitive definition of the term, but instead many different terminologies exist. The terminologies vary, for instance, in the context they are used like development co-benefits or climate co-benefits (Miyatsuka and Zusman, 2015; Ürge-Vorsatz et al., 2014).

In the IPCC's Fifth Assessment Report, co-benefits are described as “*the additional objectives, achieved by a governmental policy or measure, which intended to achieve a different main objective like mitigation*” (IPCC, 2014, Box TS. 11). The United Nations Environmental Programme (UNEP) refers to co-benefits as “*positive effects that a policy or measure aimed at one objective might have on other objectives* […]” (UNEP, 2018, Glossary). Pearce (2000) adds that co-benefits can also be referred to as “*spillover benefits*”, “*secondary benefits*” or “*ancillary benefits*” of a policy (Pearce, 2000, p.2). Miyatsuka and Zusman add, that these benefits are most important in the context of climate policy, but are not confined to that (Miyatsuka and Zusman, 2015). Bollen et al. (2009) specifically link co-benefits to climate mitigation policy when describing them as “*[a] potentially large and diverse range of collateral benefits that can be associated with climate change mitigation policies in addition to the direct avoided climate impact benefits*” (Bollen et al., 2009). Co-benefits are not uniquely linked to green or climate policy and can also refer to other forms of policy as the IPCC, UNEP, and Pearce note. Co-benefits are however mostly referred to, in the context of climate policy as they are often used in combination with mitigation costs.

The most commonly analyzed type of co-benefit in literature are health benefits mostly stemming from reduced air pollution (Deng et al., 2017). This is also noted by the IPCC as they contribute robust evidence to this co-benefit (IPCC, 2014a). Other benefit types found in the literature referring to changes in employment, crop yields or energy security or ecosystem impacts (Deng et al., 2017; Mayrhofer and Gupta, 2016). Environmental co-benefits are probably the largest but are rarely monetized (Deng et al., 2017; Griscom et al., 2017).

The different co-benefits can either be expressed in physical terms, but in some cases also in monetary units. For most co-benefits however, physical indicators are used to determine their potential. In the following the most commonly studied co-benefits health, energy security, employment and ecosystem impacts (Deng et al., 2017) will be addressed in more detail and their indicators presented to deliver a base for the decision of the benefit the thesis focusses on.

2.1.1.1 Health Benefit

Health benefits of climate mitigation are usually referring to the reduction of health infringing aspects, especially air pollution from traffic, power plants or indoor fireplaces (Perera, 2017). One of the most studied types of health benefits is coming from the reduction of air pollutants (Deng et al., 2017). Certain air pollutants can, for instance, exacerbate asthma, which affects especially children of low-income families (Tzivian, 2011) and can also increase the chances of developing asthma in young children (Jung et al., 2012). The World Health Organization (WHO) reports that exposure to specific air pollutants can increase the risk of cardiopulmonary conditions, respiratory infections and lung cancer (WHO, 2009).

Health benefits often fall under the category of environmental benefits, since they are mostly coming from the reduction of air pollutants. The category of environmental benefits is studied most often, with, however, most of the environmental benefits referring to health co-benefits from reduced air pollution (Deng et al., 2017).

To assess the health benefit from reduced air pollutants, different indicators are used. Avoided premature deaths resulting from the avoidance of different diseases provoked by air pollution are, for instance, a common indicator (Garg, 2011; He et al., 2010; Markandya et al., 2009; Vandyck et al., 2018). Other physical indicators for health benefits are “Disability-Adjusted-Life-Years” (DALYs) or “Years of Life Lost” (YLLs) (Wilkinson et al., 2009; Woodcock et al., 2009). In some cases, these physical indicators are monetized and can then also be expressed per emission abatement.

To estimate the impact certain air pollutants have on the human body, studies apply health-impact and health / concentration-response functions. These functions determine how significant certain air pollutants are in, for instance, provoking or worsening certain diseases like cancer or asthma. To determine the impact of air pollutants on the number of premature deaths, these functions are one crucial determining factor. One study found that the choice of the concentration and health response functions of air pollutants has an effect on the avoided premature deaths as large as 56% (Anenberg et al., 2011). The amount of benefit the studies contribute to health from a reduction of air pollutants is therefore based on many assumptions taken by the author.

Another crucial assumption for air pollution benefits comes from their monetization. When air pollution benefits are monetized, the monetization is achieved by applying a Value of Statistical Life (VSL) on the avoided premature deaths (Markandya et al., 2018; Vandyck et al., 2018). The VSL is based on another concept, the “Willingness to Pay” (WTP). The WTP refers to an infinitesimal reduction in mortality risk and is defined as the marginal rate of substitution between wealth and mortality risk over a short time period (Hammitt, 2000). In cases where no country-specific WTP estimate exists, VSLs are taken from a base country and then adjusted based on the country GDP or another wealth indicator like real income per capita of the target country (Vandyck et al., 2018).

Using VSLs to monetize premature deaths is criticized due to the ethical considerations it could provoke. The way the VSL is calculated results in countries with a high GDP having the value of life valued higher compared to countries with lower GDP. Ürge-Vorsatz et al. (2014) therefore suggest, to just use the physical indicator to measure health benefits (Ürge-Vorsatz et al., 2014). By contrast, Markandya et al. (2018) justifies using VSLs, despite the ethical considerations, since they are a widely known method and enable the user to reflect health costs in the way such costs are covered in each region (Markandya et al., 2018). Another advantage of the monetary indicator is, that it allows for the comparison of co-benefits on the basis of the cost of making the abatement (Markandya et al., 2009). Furthermore, as explained above, the inputs used in the calculation of the VSL are not considered unethical, it is rather the interpretation of the value that results in the ethical considerations.

2.1.1.2 Energy Security

The co-benefit of energy security is highly dependent on the country it is referring to. As Ürge-Vorsatz et al. (2014) said, the same benefit for one side can be considered positive, and for another side negative (Ürge-Vorsatz et al., 2014). For instance, a reduction of oil importers due to increase renewables in a country could result in increased energy security for the importer, but at the same time reduced energy security for the exporter due to limited demand. Due to that, energy security is hard to define and therefore also hard to measure, resulting in only a few studies estimating the co-benefit of energy security (McCollum et al., 2013).

Papers analyzing energy security choose different indicators to account for different country contexts (Sovacool and Brown, 2010). Sovacool and Brown (2010) categorized the co-benefit of energy security in the three categories ’ availability, affordability, energy and economic efficiency and environmental stewardship with each of them having different indicators as shown in the table below (Sovacool and Brown, 2010).

Table 1: Definition and indicators of energy security (Sovacool and Brown, 2010)

Criteria	Underlying Values	Explanation	Metrics
Availability	Independence, diversification, reliability	Diversifying the fuels used to provide energy services as well as the location of facilities using those fuels, promoting energy systems that can recover quickly from attack or disruption, and minimizing dependence on foreign suppliers	Oil import dependence; Natural gas import dependence; Availability of alternative fuels
Affordability	Equity	Providing energy services that are affordable for consumers and minimizing price volatility	Retail electricity prices; Retail gasoline/petrol prices
Energy and Economic Efficiency	Innovation, resource custodianship, minimization of waste	Improving the performance of energy equipment and altering consumer attitudes	Energy intensity; Per capita electricity use; Average fuel economy for passenger vehicles
Environmental Stewardship	Sustainability	Protecting the natural environment and future generations	Sulfur dioxide emissions; Carbon dioxide emissions

The table illustrates the many different metrics that could be used to assess energy security. Climate policy could result in energy security benefits through independence and diversification, due to a reduction in energy imports, slower depletion of non-renewable resources and increasing the diversity of energy sources (Cherp et al., 2013; Jewell et al., 2013; Kruyt et al., 2009). At the same time, they could however also result in innovation reducing the energy intensity of the economy (Sovacool and Brown, 2010). Depending on the chosen metric for energy security, many different interpretations could arise further complicating the comparability of the benefit to others like health.

McCollum et al. (2013) and others argue that the term of energy security in regard to co-benefits does not refer to the ability of GHG mitigation to reduce the dependency on energy imports but rather to the energy security resulting from a more resilient and diversified energy portfolio by including more low carbon technologies and energy efficiency improvements (Bundesregierung Deutschland, 2016; Deng et al., 2017; McCollum et al., 2013). While some studies like Bertram et al. (2019) and Jewell et al. (2016) only focus on the dependency on one energy carrier like oil (Bertram et al., 2019; Jewell et al., 2016), others chose a more comprehensive approach and created a compound diversity indicator covering multiple energy carriers, geographical locations and import balance trying to capture multiple dimensions of energy security (McCollum et al., 2013).

These many different metrics combined with the consideration, that the same “benefit” can be perceived by one side as positive and by the other as negative, make it very hard to apply this co-benefit in different countries and to compare it. Not many studies quantified the co-benefit of energy security, resulting in medium to low evidential base (IPCC, 2014a).

While a reduction of air pollutants could be felt relatively intermediate to the implementation of the mitigation measures, the effects for energy security take longer. Most of the effects of energy security are emerging later than 2030. In the short-term mitigation efforts reduce the deployment of coal which is counterbalanced by the increase in renewables (Jewell et al., 2013). Only after that, the effect of a reduction of energy imports can be felt making this co-benefit also less relevant for this thesis (von Stechow et al., 2015).

2.1.1.3 Employment

There is limited literature on the impact of employment or job creation resulting from GHG mitigation in developing countries. There are estimates on employment and job creation of green jobs by for instance investing in renewable energy sources in Europe and the US showing a significant increase in green jobs from investments in renewable resources (Day et al., 2018; United Nations Environmental Programm (UNEP), 2000; Wei et al., 2010; Yi, 2013). For developing countries, studies estimate the effect of climate policies on job creation even larger due to the higher need for investments in mitigation technologies with for instance ADB and ADBI (2013) estimating a significant green job creation for Asia (Sovacool, 2017). Due to the lack of data for this benefit for China and India in 2030. This co-benefit was not studied in this thesis.

2.1.1.4 Ecosystem Impact

The impact on the ecosystems is one of the most mentioned co-benefits, also since health benefits coming from a reduction of air-pollutants also fall under this category (Deng et al., 2017). A reduction of ecosystem impacts or biodiversity losses is often a result of reduced air pollution or land use competition (IPCC, 2014a). The effects on the ecosystems are however not often monetized. In some cases, they are shown aggregated together with health benefits like the case for Vandyck et al (2018), who aggregated the co-benefit from reduced air pollution on health and crop yields (Vandyck et al., 2018). Monetized co-benefit estimates exclusively from ecosystem impacts are however hard to find. This co-benefit was therefore not analyzed separately in this thesis. In cases where the benefit was included in the benefit on health like in the example from Vandyck et al. (2018), the aggregate of both benefits has been used without separating them due to the small impact the changes in crop yields have, compared to the health estimates from reduced premature deaths (Vandyck et al., 2018).

2.1.2 Adverse Side Effects

While the focus in the literature is on the co-benefits of climate mitigation, the same concept also applies to the "*indirect negative consequence of climate policy*" (Pearce, 2000, p.2). These negative consequences are described by the IPCC as "*adverse side effects*" (IPCC, 2014, Box TS. 11).

Most current co-benefit analysis do not separately account for the negative ancillary costs associated with climate mitigation, which is also referred to as co-costs (Ürge-Vorsatz et al., 2014). Examples of co-costs are for instance referring to job losses in a certain economic sector due to the phase-out of certain technologies because of climate mitigation efforts in another sector (Ruth, 2011). The IPCC further gives examples for co-cost referring to, for instance, reduced road safety from silent electric vehicles or rebound effects of climate mitigation which can be measured by financial or physical indicators (IPCC, 2014a).

In studies that are quantifying co-benefits, the concept of co-cost is rarely discussed. These studies calculate the net-benefit and are therefore already implying that the co-benefits are larger than the co-costs. The concept of co-cost, however, does not necessarily refer to the direct costs of certain measures exclusively but the same as co-benefits refer to additional impacts like mentioned above. Since the literature rarely provides specific co-cost estimates but rather net-benefits, only the net-benefits have been used for this thesis as it is assumed, that their estimate is already including potential co-costs.

2.1.3 Finding a Common Indicator for Different Co-Benefits

As the previous illustration of the most found co-benefits showed, is finding one common indicator that fits multiple different co-benefits difficult. The previous chapters illustrated the many different indicators used to quantify co-benefits. One potential indicator to aggregate multiple co-benefits could be, to aggregate them under the same monetized unit. Some co-benefits are however hard to monetize and for others, the monetization leads to ethical concerns like the case for health benefits. Especially the dependence of co-benefits on local circumstances reduces the possibility to summarize co-benefits under one indicator for larger regions.

One attempt of aggregating multiple co-benefits on a global level was conducted by McCollum et al. (2013) who aggregated two co-benefits, air pollution, and energy security, under the indicator of percentage change of global GDP (McCollum et al., 2013). Aggregating multiple co-benefits for larger regions would require to also aggregate the indicator and with that reducing the impact and persuasiveness of the results (von Stechow et al., 2015).

2.2 Integrated Assessment Models and Emission Pathways

Integrated Assessment Models are an important part of current policy decisions since they allow for estimating the potential impact of the policy on the economy and gives cost estimates for meeting the policy objective. For this thesis, an IAM database provided emission and cost data for multiple mitigation scenarios which are explained in more detail in Step 2 of the research (section 3.2).

IAMs integrate inputs from different disciplines like economics, physical climate simulations, and others. Over time IAMs developed and became more sophisticated. The IPCC describes IAMs in their latest report as "*simplified, stylized, numerical approaches to represent enormously complex physical and social systems"* (IPCC, 2014b, p422). Some important input assumptions of IAMs refer to population growth, baseline economic growth, resources, technological change, and the mitigation policy environment (IPCC, 2014b). IAMs can generate sophisticated scenarios including many different price affecting factors to allow for finding an "optimal" prioritization of climate mitigation options. When an external temperature goal, like 1.5 °C, is introduced into the model, it deploys all mitigation measures in any country in the world at any point over a period, so that the temperature goal is globally achieved in a cost-effective way (Hare et al., 2018).

Integrated assessment models differ in multiple dimensions ranging from their sectoral coverage to solution algorithms, representation of GHG emissions and GHG sources, energy demand and supply sectors, population and GDP baselines, and assumptions on techno-economic parameters (Bruce et al., 1996). They can, however, be broadly grouped into two categories, Partial Equilibrium (PE) models and General Equilibrium (GE) models.

Examples for PE models are for instance AIM, GCAM, IMAGE, POLES, DNE21. PE models describe processes and markets in one or more sectors in detail. These include, for instance, the energy sector including energy demand by economic sectors and technological specifications. They treat however the rest of the economy exogenously. Their assumptions usually include price-elastic demand in goods and services in the represented sectors. These models further typically maximize consumer and producer surplus or minimize production costs of sectors over time (Kriegler et al., 2015).

Examples for GE models include IMACLIM, MERGE, MESSAGE, REMIND and WITCH. GE models cover the full economy but portray all sectors in less detail compared to the PE models. GE models can apply a dynamic recursive approach or intertemporal optimization. Dynamic recursive GE models identify market equilibria for every point in time with assumptions on how the economy will develop over time. They are inherently myopic and can display a detailed description of the sector composition over a small time period. Intertemporal GEs on the other hand focus on the dynamics of investment in production capital under foresight about future production and consumption. They describe a closed economy but can only explore one or two aggregated sectors due to their intertemporal optimization. Both GE and PE models can display a large variety of low-carbon supply options. Some GE models, however, include a noticeable lower number of options than PE models (Kriegler et al., 2015).

General equilibrium models (GE) express mitigation costs as losses in welfare, consumption or GDP, where the first two metrics directly measure the impact on private income and consumption (Kriegler et al., 2015). GDP is a less satisfactory metric as it is a measure of output as opposed to the other two metrics, including, besides consumption, also investment imports, exports and government spending (Paltsev and Capros, 2013). Partial equilibrium (PE) models have a narrower definition as they are not able to include feedbacks on economy-wide production and consumption, but rather express mitigation costs in terms of consumer and producer surplus. Some models can also illustrate the additional energy systems costs compared to the baseline as a measure. GE and PE models are in terms of their cost estimates not fully comparable. Due to their cost definitions, PE models generally show lower mitigation costs compared to GE models with certain exceptions (Kriegler et al., 2015).

Most of the GE models give the intertemporal mitigation costs as the net present value of consumption losses as a percentage of net present value consumption in the baseline. The intertemporal mitigation costs from PE models are given for GCAM, IMAGE and POLES in terms of the net present value of the area under the marginal abatement cost curve (MACC) and in terms of additional energy system costs for DNE21 as a percentage of net present value GDP in the baseline (Kriegler et al., 2015).

Another major difference between different IAMs and scenarios is linked to how they deal with negative emissions. Negative emissions are a very common method applied by most IAMs, especially for ambitious climate scenarios like for 1.5 or 2°C. The reason why negative emissions are applied in most IAMs is, that reaching those climate targets without negative emissions would require massive cuts in emissions already in the short term (Carbon Brief, 2018). Depending on the significance the IAM gives negative emissions at the end of the assessment period, the amount of required reduction in the earlier parts of the assessment period change.

One major feedback missing from IAMs are economic damages and reduced growth as a result of climate change which excludes some potentially significant implications of climate change (Carbon Brief, 2018). Another type of cost or rather avoided costs are co-impacts. These co-impacts are often also a feedback IAMs are so far not able to project (PBL, 2014). Especially the inclusion of these impacts could drive down the estimated mitigation costs significantly (Stern, 2016). Due to all these limitations, some authors raise the question, whether IAMs should be used to inform policymakers about the cost estimates so far in the future (Pindyck, 2013; Rosen and Guenther, 2015) or if they are the wrong tool to do that (Anderson and Jewell, 2019).

2.2.1 Mitigation Costs

IAMs can estimate the costs of a certain policy, like for instance reaching a certain mitigation pathway. These costs are referred to as mitigation costs which definition differs from model to model. The definition changes due to the different capabilities the models possess in estimating the total cost of a policy. PE models calculate mitigation costs in terms of sector cost mark-ups or reduction of consumer and producer surplus. GE models can display mitigation costs in terms of production losses, consumption losses or welfare measures. As explained in the previous chapter, PE models have a narrower definition of the sectors they are able to portray than GE models, leading to generally lower cost estimates (Kriegler et al., 2015).

The total mitigation costs of an IAM are one major model output and therefore depend on many different variables and processes making it difficult to describe exactly how the total abatement costs are generated (PBL, 2014). The total mitigation cost estimates provided by the IAM database do not allow for identifying the cost of individual mitigation measures (IIASA, 2019). This missing transparency is also described as one of the major drawbacks of integrated assessment models stemming from the complexity of these models. However, such complexity is required to increase the accuracy of modeling such complex systems as the climate (Kelly, D. L., & Kolstad, 2000). IAMs, therefore, represents a tradeoff between complexity and transparency.

For this thesis, two different PE models have been selected since their cost calculation allows for creating a Marginal Abatement Cost Curve (MACC) for 2030 which would not be possible for GE models due to missing input data. In the following section, MACCs are described and differences between different types of MACCs portrayed.

2.2.2 Marginal Abatement Cost Curves

Marginal Abatement Cost Curves are often used as a representation of abatement costs and display the mitigation costs as marginal costs of reducing the last unit of emission abatement in a certain year (Kesicki, 2011).

The IAM itself uses regional fuel-specific MAC curves and estimates, based on these curves aggregated regional demand and supply curves to calculate and market equilibrium permit price (or carbon price) in an international trading market, its buyers and sellers as well as the domestic and external abatement resulting from that, per region (PBL, 2014). The resulting curve is usually defined as a policy scenario and is compared to a reference scenario (REF) where no policy is applied. In order to display the marginal abatement cost against a baseline development, the baseline has to be developed without any CO_2 constraint in place (Kesicki, 2011). The artificially set carbon price in the policy scenario is the main driver that determines the mitigation costs in IAMs (den Elzen and Lucas, 2003). The mitigation pathway of IAMs is therefore also always more expensive than the reference scenario where no policy was applied (Hare et al., 2018).

MACCs were often used due to their visual representation of cost and benefits combined. There are however different ways to construct a MAC curve.

Figure 3 below shows a MAC curve constructed as a histogram bottom-up approach based on expert-based estimates in a measure by measure manner on the left panel and a top-down projected mitigation costs profile estimate in form of a curve, derived by macro-economic modeling, on the right panel for China (Bockel et al., 2012). Top-down models are used to investigate the impact of macroeconomic policies for mitigation purposes whereas the bottom-up models are rather used to study options that have sectoral and technological implications (UNFCCC, 2006).

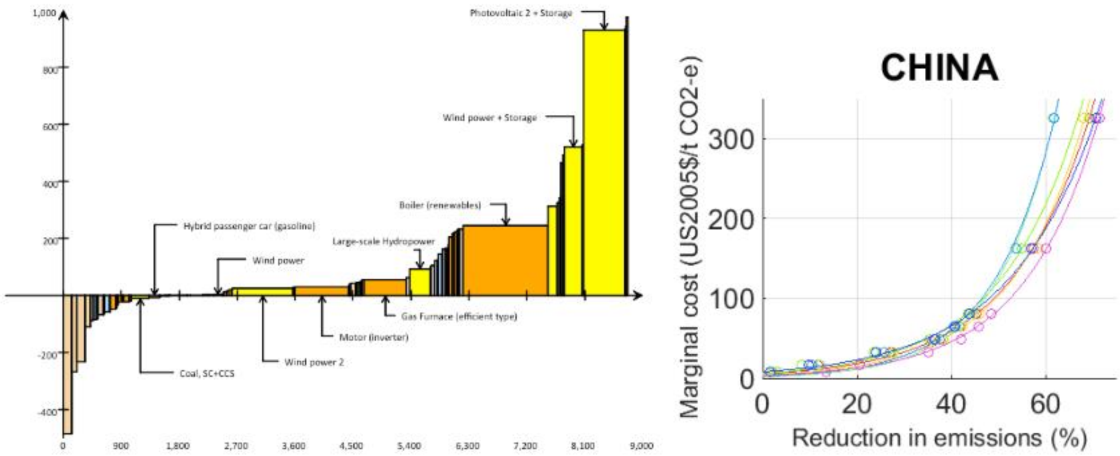

Figure 4: Left panel shows a MACC for China in 2030, the right panel shows the projected mitigation cost profile generated by macro-economic modeling, China, 2030 (Alexander et al., 2015)

Both types of MACCs show the marginal abatement costs for different amounts of emission reductions. One parameter influencing the marginal abatement cost is the choice of the discount rate. The cost perspective of the assessment influences the choice of the discount rate used for the calculation of the MACC (Kesicki, 2011). **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the formula for estimating the specific CO_2 emission costs, often also referred to as marginal abatement cost (Blok and Nieuwlaar, 2016).

Equation 1: Marginal abatement cost formula (Blok and Nieuwlaar, 2016)

$$C_{spec,CO2} = \frac{\alpha * I + C - B}{\Delta M_{CO2}}$$

Where the discount rate (α) and the annual investment (I) results in the annual capital cost, (C) the annual operation and maintenance costs, (B) the annual benefits and (ΔM_{CO2}) as the annual amount of avoided CO_2 emissions. A low-interest rate of 3.5%, for instance, reflects society's preference over time while a higher discount rate of 10% or higher is a better measure for the cost a private individual has to face when making investment decisions (HM Treasury, 2003; Kesicki, 2011). A lower discount rate, therefore, reduces the marginal abatement costs.

For both types of IAMs it is true that under simplified assumptions for a marginal abatement cost curve adding up all emission reductions before the desired emission target multiplied by the cost for these reductions (which is equivalent to the integral of the MACC) would lead to the total cost of the abatement when the MACCs provides cumulative emission reductions. Paltsev and Capros however also note, that this definition of total abatement costs is very simplified and also only captures part of the cost for the actual policy (Paltsev and Capros, 2013).

While the expert-based MACCs can have mitigation measures with negative costs, these are not present for model derived MACCs. These options are often called "no-regret" options as they result in cost savings instead of costs. These options are often increasing the overall energy efficiency (e.g. insulation in buildings, more efficient electric appliances or cars), reduce emissions and have higher cost savings than direct costs from a societal perspective (Wagner et al., 2012). In MACCs derived from IAMs however, this negative cost emission abatement is missing, and every abatement has a cost attributed to it. This is resulting from the way IAMs are estimating the cost of a mitigation scenario. As previously explained, the mitigation scenario in an IAM where a carbon price was applied is compared to a reference scenario, where no additional or increasing carbon price was applied. The mitigation scenario will therefore always be more expensive than the reference and due to that do not show negative costs.

Due to the comparison of the two pathways, the mitigation pathway is always more expensive than the reference. This however also results in the model derived cost curve to always start at zero cost for zero emission abatement. Since these models assume rationality, no abatement has no costs associated with it, which is not the case in reality, especially when you consider the negative externalities of not reducing emissions (Hare et al., 2018). To arrive at negative costs, the IAM would need to consider that it would be economically rational to add negative external costs of fossil fuels or co-benefits to the price consumers pay for energy, but they usually do not do that yet (Hare et al., 2018).

2.2.2.1 Expert-based MACC

Expert-based MAC curves - often also technology cost curves - are based on assumptions developed by experts on the baseline emission development as well as the CO_2 reduction potential and the accompanying costs of individual mitigation measures. The width of each bar in panel a) of **Fehler! Verweisquelle konnte nicht gefunden werden.** represents the potential emission abatement of the technology in a target period and the height of the bar the average marginal costs. The average marginal cost of the measure multiplied by its abatement potential in ton of CO_2 per year, resulting in the total costs required for the specified amount of emission reduction in a certain year (Bockel et al., 2012). The ranking of the measures follows from the cheapest to the most expensive measure.

The main advantage of expert-based MACCs is that their visuals seem to be easy to understand. The marginal costs and abatement potential of measures can easily be visualized. This allows for knowing which measures are required to reach a certain mitigation level. However, many limitations of expert-based MACCs persist, which may lead to difficulties in interpreting the MACC. These limitations will be further illustrated below.

One of its drawbacks comes from the above-mentioned simplification of certain aspects resulting in partly implausible estimates. In many curves, for instance, only one cost level is assigned to certain technologies in a certain year, which is not representative of, for instance, renewable energy technologies, which can have vastly different cost values depending on, for instance, their power generation capacity. This can, however, be accounted for by drawing multiple curves. The selection of technologies following the probability of realization depends on the choice of the expert. Expert-based MACCs, therefore, do not necessarily portray all potential options but rather illustrate a certain scenario.

Other possible influencing factors like technology costs, energy prices or demand development are also not specifically accounted for in expert-based MACCs. Additionally, expert-based MACCs miss to account for certain interactions like for instance the interaction of emission abatement over time, meaning that the implementation of a certain measure reduces the abatement potential of following measure or interactions between different mitigation measures themselves (Kesicki, 2011). To represent these interactions correctly, the baseline for the remaining mitigation measure would need to be adopted after the implementation of a previous measure. The decarbonization of the electricity would, for instance, reduce the abatement potential for the insulation of electrically heated homes. When these interactions are not accounted for, problems like double-counting could lead to an overestimation of the abatement potential (Kesicki and Ekins, 2012). The risk for double-counting from interactions between measures is smaller in model-derived MACCs since they don’t rely on the individual abatement of technologies, but rather have a systematic approach.

2.2.2.2 Model-derived MACC

Energy models, like for instance economy-oriented top-down integrated assessment models, are also able to derive the cost and potentials to create marginal abatement cost curves (den Elzen and Lucas, 2003). Other than for the previous type, these cost curves are not based on expert input on specific technologies. The abatement curves are generally derived by summarizing the CO_2 price from different model runs varying in the strictness of their CO_2 limits or by summarizing the emission level resulting from different CO_2 prices. However, the focus on absolute terms of emissions neglects the technology-specific aspect of the expert-based MACC, which is why model derived MACCs lack the technologic detail the expert-based MACCs offer (Kesicki, 2011).

The main advantage distinguishing top-down MACCs from the bottom-up expert-based MACCs is their ability to take macroeconomic interactions like feedbacks, rebound or spill-over effects into account as well as the effects of climate mitigation policies on income and trade. The system boundaries are therefore extending to further than the power sector in contrast to most expert-based MACCs. Since models usually maximize welfare from a social perspective, they are, in contrast to expert based MACCs, also able to accumulate sectoral abatement curves (Kesicki, 2011).

The main disadvantage of the top-down model derived MACCs is, however, their inability to represent technology specific detail. They are therefore not able to illustrate the measures required for certain emission abatement. The key strengths and weaknesses of model-derived MACCs have been summarized in Table 2 below.

Table 2: Strengths and weaknesses of model-derived marginal abatement cost curves (adapted from Kesicki, 2011)

Strengths	**Weaknesses**
Macroeconomic feedbacks and costs considered	No technological detail in representation of MACC
Interactions between measures included	
Consistent baseline	
Intertemporal interactions included	
Uncertainty assessment possible	

It is, however, important to note, that both types of MACCs are used in different contexts. One type of construction of the MACC is therefore not inherently superior over the other.

2.3 Impact of Co-Benefits on Climate Policymaking

The previous sections illustrated that one major drawback of both IAMs and MACCs is, that ancillary effects like co-benefits are usually not included in them. This section describes the effect an introduction of the co-benefits would have on the different types of MACCs.

Climate policymaking is generally not aimed towards maximining the level of abatement, but rather to minimize the cost of previously set abatement levels. In this case, co-benefits would need to be compared to the abatement cost and therefore affect the slope of the marginal abatement cost curve (Nemet et al., 2010).

When visualizing this interaction with expert-based MACCs, the impact of the inclusion of co-benefits in the MACC can be made more specific. Figure 5 below shows the implications of an introduction of a co-benefit of 20 USD/tCO_2 in the exemplary expert-based MACC.

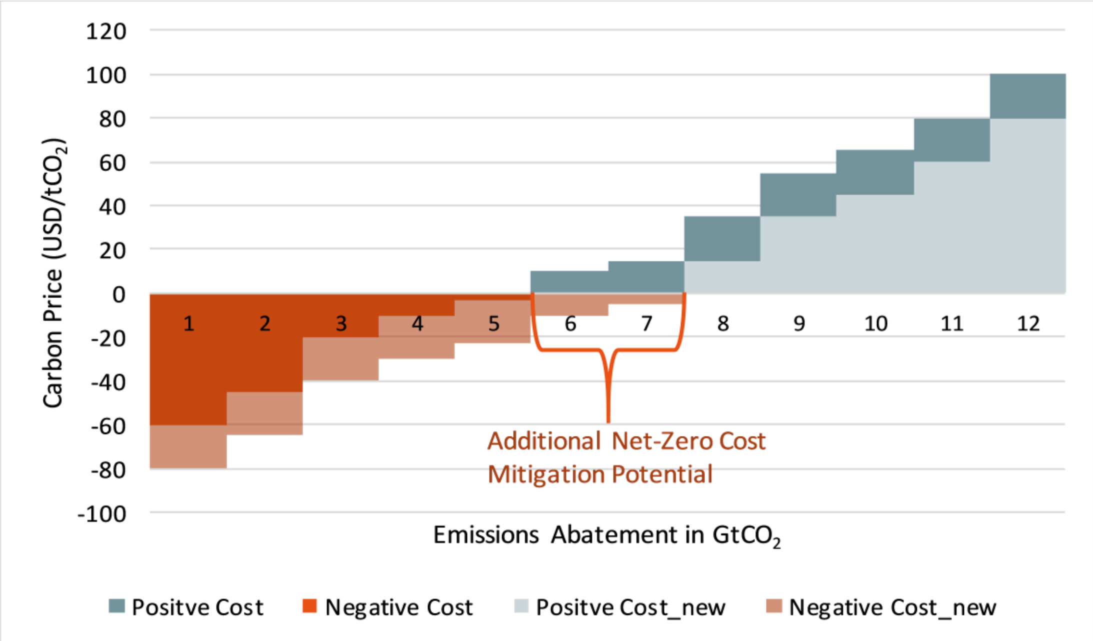

Figure 5: Impact of an equally distributed co-benefit of 20 USD/tCO_2 on an exemplary expert-based MACC

As explained in section 2.2.2.1, expert-based MACC consists out of different mitigation measures that each have a certain level of emission abatement potential per year and an associated cost per ton of CO_2 abated. If co-benefit values per mitigation measure would be available, a specific co-benefit value could be attributed to individual mitigation measures. If such information is not available and no assumptions are taken, the co-benefit has to be subtracted from each measure equally, resulting in a downward shift of the whole curve in the margin of the co-benefit.

When the introduced co-benefit is larger than the positive cost of the measures (in Figure 5, measures 6 and 7), the mitigation options with previously positive costs, become measures with negative costs. The amount of mitigation potential these measures would provide now has negative costs associated with it, resulting in these measures to become the new net-zero cost mitigation level due to the introduction of co-benefits.

Figure 5 below shows how the addition of the co-benefits to the model derived MAC could be interpreted as a downward shift in the abatement cost curve. This shift reduces the abatement cost so that the cost of a certain abatement level q* falls from p* to p’, making the cost of the policy cheaper for the same level of pollution abatement. However, instead of studies giving a new explicit value for p’, most studies rather give p* and state an overstatement of the policy cost (Nemet et al., 2010). In this case, however, the co-benefit did not reduce the full curve equally but distributed more co-benefits to the lower cost part of the curve than the higher cost part. This could, for instance, be based on assumptions attributing the lower cost pollution a higher amount of co-benefit, for instance, due to higher air pollution levels caused by the lower-cost fossil fuels.

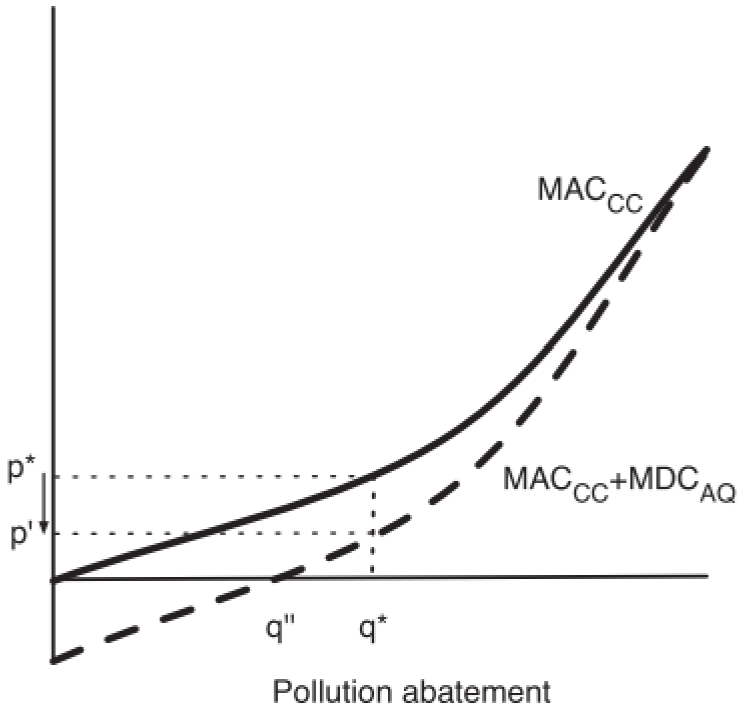

Figure 6: Effect of including co-benefits on model-derived marginal abatement cost curve of climate policy (Nemet et al., 2010)

While in expert-based MACCs the individual mitigation measures that result in the additional potential are visible, this is not possible in the model derived MACCs shown in Figure 6. In these MACCs, the introduction of a co-benefit leads to a downward shift of the curve as explained above. When the co-benefit is introduced in model-derived MACCs, the whole curve shifts downward, depending on the type of distributing the co-benefit across the curve. For an equal distribution, the whole curve would be shifted downwards equally. Or as shown in Figure 6, an unequal distribution would shift parts of the MACC downward differently. Since the model derived MACCs do not have negative costs before co-benefits are introduced, the emission levels at net-zero costs from introducing the co-benefit is equal to the part of abatement which has negative costs after the implementation. This is equal to the point q^{II} in Figure 6**Fehler! Verweisquelle konnte nicht gefunden werden.**.

2.4 Delimitations of the Research

To define the scope of the research several boundaries had to be decided. These include the country selection, the analyzed co-benefit, the target year, the covered sectors and or fuels as well as the emission and cost estimates used. The following paragraphs will introduce the boundaries.

Country selection

The selection of the countries was mainly determined by their potential for co-benefits and if they are an Annex II country. It is especially these developing countries with high levels of pollution that could benefit the most from the potential cost reduction co-benefits could offer. The selected countries are China and India. Both regions are key emitting countries and have to face high air pollution levels and could therefore greatly benefit from co-benefits (Roston and Tartar, 2019).

Co-benefit selection

A detailed assessment of multiple co-benefits is not possible due to data limitations coming from their heterogeneity and the number of different indicators used. An assessment of multiple co-benefits is further complicated by focusing on whole countries rather than a more local context. The selection of the co-benefits followed first and foremost their data availability for monetized benefit estimates. The required data were monetized co-benefits estimates in Dollar per ton CO_2 avoided or data, that would allow for calculating this indicator like the number of premature deaths avoided.

The co-benefit on health resulting from reduced air pollution was selected as it is considered to be highly impactful and agreed upon under scientists (IPCC, 2014a). The co-benefit from reduced air pollution on health delivered the most quantitative monetized estimates and is also one widely reviewed co-benefit. Additionally, multiple review studies indicate that health co-benefits could be among the largest of all the co-benefits introduced in Section 2.1.1 (Ürge-Vorsatz et al., 2014). Other potentially impactful benefits like energy security, job creation or ecosystem impacts which are described in the previous sections could have a significant impact, are however less studied and monetized in current literature and therefore lack the required data for the assessment.

Target year

The target year for this thesis was set to be the next milestone year of 2030. This target year allows for a further increase in ambition in the period to 2050. Due to that, only co-benefit studies were used in this assessment, that estimated the co-benefits for the specific region in 2030 or included 2030 in their assessment.

Sector and fuels

Most of the identified co-benefit studies focused on either the power sector or economy-wide assessments. The number of sectors or fuel-specific co-benefit estimates was limited. Therefore, only economy-wide and power sector-specific co-benefits have been aggregated per country.

Emission and cost estimates

Since recently conducted expert based MACCs for China and India were not openly available, the estimation of a MACC in 2030 had to be based on data from IAMs. The estimation of a MACC in 2030, which is explained in Step 2 of the research, required openly available data from integrated assessment models. Specifically, the emission abatement between a mitigation scenario and a reference scenario, the carbon price to achieve the reduction and most importantly the area under MACC, which represents the total mitigation costs for the mitigation scenario. Most GE IAMs are determining the mitigation costs more in an integrated look on the economy as a loss of consumption. The assessment was therefore limited to the PE models using the area under MACC as their mitigation costs assessment (Kriegler et al., 2014).

The ADVANCE project database was selected as it was a recently conducted study focusing on comparing many different IAMs and exploring different Paris-compatible emission scenarios (PIK, 2017). The two PE IAMs selected for this study were IMAGE 3.0 and POLES ADVANCE as they were able to provide the necessary input data for estimating a MACC in 2030.

The mitigation scenario for this study is referring to a 1.5˚C pathway starting with mitigation action in 2020.

2.5 Overview of the Quantification Steps

Figure 7 below illustrates the steps of the research based on the connections of the theoretical framework and key concepts illustrated in the previous section shown as the corresponding chapter numbers in brackets. The figure further displays the analytical steps conducted in this thesis.

In Step 1 (section 3.1) of the research, data on co-benefits was collected. For this several co-benefit modeling studies have been collected and scanned for monetized values on the health benefits from reduced air pollution in China and India in 2030. To fill gaps in the data, also proxy data was extracted allowing for estimating the monetized benefit based on the data given.

In Step 2 (section 3.2) emission and cost pathways were extracted from the ADVANCE Project IAM database. The estimation of the MACC in Step 2.1 (section 3.2.1) required the mitigation gap and the carbon price, as well as the total abatement costs as “area under MACC” indicator in 2030. These points were used to estimate a MACC for a 1.5˚C pathway.

Step 3 (section 3.3) synthesized the input parameters delivered by the previous steps. The cost curve constructed in Step 2: Quantification of Emission and Cost Pathways.1 was adjusted with the in Step 1: Quantification and Aggregation of Monetized Health Co-Benefits extracted co-benefits values to create a by co-benefits adjusted marginal abatement cost curve. The curve was adjusted based on Median as well as the 10th and 90th percentile range of the extracted of co-benefits.

In Step 4 (section 3.4) of the research, the emission level at net-zero cost from the inclusion of co-benefits was estimated and the cost reduction of the total abatement costs were calculated. This value describes the amount of emissions that could be achieved at net-zero costs when considering co-benefits. The impact, different types of distributing the co-benefit have on the MACC, was studied as well.

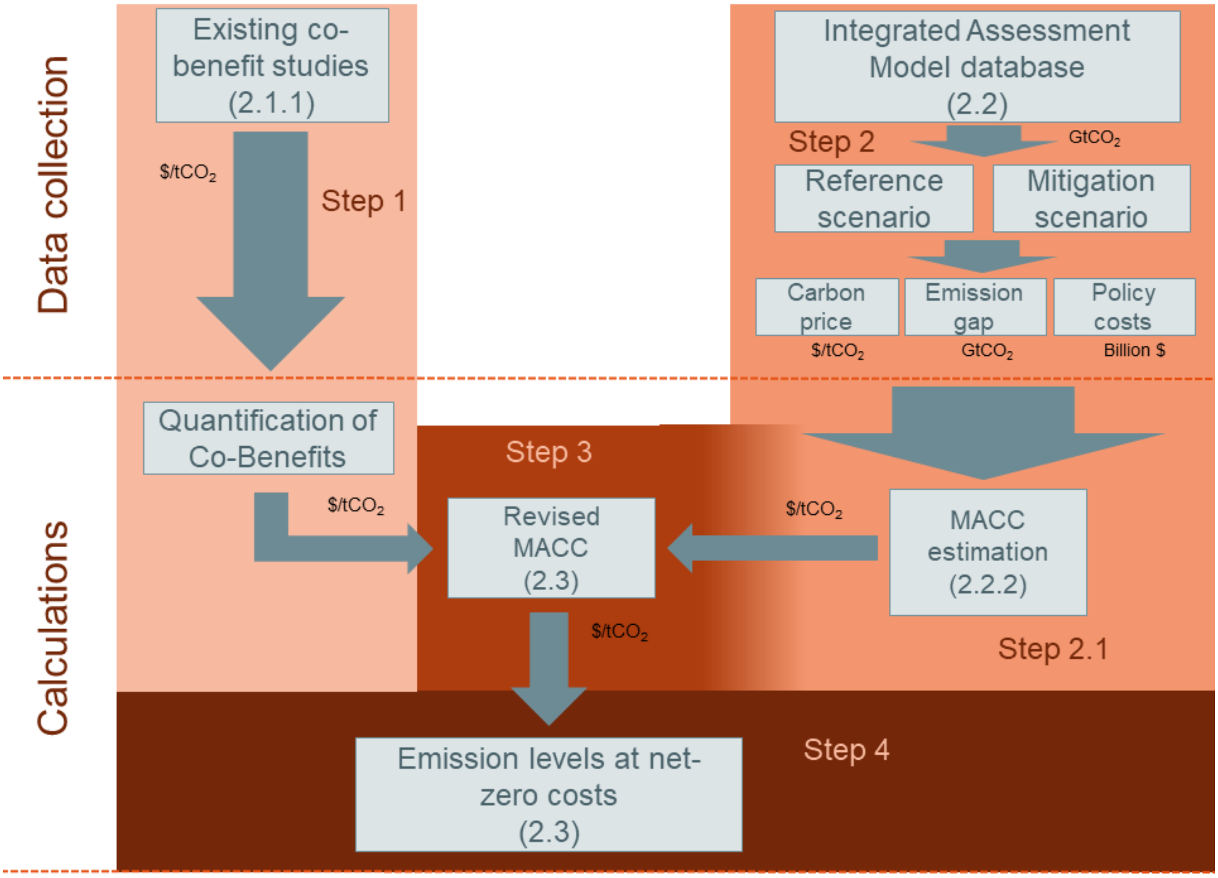

Figure 7: Steps of the research

3 Methods

3.1 Step 1: Quantification and Aggregation of Monetized Health Co-Benefits

The first step of the research illustrated in Figure 6 refers to the collection of the co-benefit values from literature. This section illustrates the data collection and how the input data was processed.

Since the co-benefits are combined with a marginal abatement cost curve for the year 2030, the co-benefit estimates also had to refer to that year. First, co-benefit studies were focused that provided co-benefit values specifically for 2030. To fill data gaps however, the focus was later extended to studies, that covered a larger assessment period including the target year 2030.

Literature was scanned to collect quantifiable health co-benefit values in China and India for the year 2030. The desired unit of the co-benefit was the monetized health benefit in $_{2018}$US Dollar per ton of CO_2 avoided ($_{2018}$\$/t CO_2). In many cases, however, this measure was not readily available. The studies either used different currency base years or did not monetize the benefit.

To fill data gaps, data was extracted from the papers that allowed to calculate the monetized co-benefits per emission abatement. The data of Dollar per ton CO_2 were often given in a table but also in the form of graphs. In the latter case, the data was measured and extracted from the graphs.

Another important consideration for the choice of the co-benefit values was that the value was resulting from a 2°C or 1.5°C mitigation pathway (MIT). In Step 2 of this research (section. 3.2), the identified values are used to reduce the mitigation cost for an emission pathway, resulting in a global average temperature rise of 1.5°C. It was first attempted to collect co-benefit estimates based on a specific emission reduction in line with the temperature target. Due to data limitations however, the scope was broadened to include co-benefit estimates based on 2°C pathways. Due to the higher amount of abatement in a 1.5°C scenario, the benefit per abated emission would be lower than for 2°C pathways. Since the co-benefit used in this thesis is aggregated from co-benefit estimates from both temperature targets, the applied health co-benefit using just estimates for 1.5°C would be lower.

When the studies were not able to directly provide the monetized benefit in the required data format, data were extracted to allow for the calculation of the benefit. Especially data on the avoided emissions and a value estimating the resulting co-benefits, in the form of avoided premature deaths, was required to estimate the physical co-benefit per ton of CO_2 avoided. The monetization of these physical indicators was achieved by applying country-specific VSL estimates from Vandyck et al. (2018).

Table 3: Data requirements for manual benefit calculation

Emission data	**Co-benefit estimates**	**Monetization**
BAU and MIT (tCO_2)	Avoided premature deaths	Applied VSL
Change compared to BAU (%)		

As mentioned in the previous sections, co-benefits are highly heterogeneous due to the uncertainty regarding the balance of co-benefit and negative co-impacts as well as the case specificity of the co-benefits (von Stechow et al., 2016). The values of extracted co-benefits are therefore ranging from low to high estimates. Since some outliers with extremely high estimates compared to the other studies would increase the average of the data points by such a degree, that the average would not be representing the majority of the datapoints anymore, it was decided that a Median estimate would represent the range of identified co-benefit values better than an average. To further represent the range of values, a 10^{th} and 90^{th} percentile was taken beside the Median. These three estimates were taken per country and are further referred to as "co-benefit categories".

The identified co-benefit values are mostly referring to the health benefit from reduced diseases provoked or worsened by air pollutants. One study included, besides health benefits, also other indices in their values like an increase in crop yields which are also influenced by the reduction of air pollutants. As a result, the values from this study are larger than estimates focusing only on the health benefit. However, the calculated benefit on crop yields was significantly smaller than the estimate on the health benefit for this study (Vandyck et al., 2018). For this reason, the aggregation of both values did not significantly alter the estimation and was included in this analysis. Furthermore, by using a median value instead of an average, these small inaccuracies do not have a significant impact on the co-benefit values applied in this thesis.

3.1.1 Monetization of Co-Benefit Estimates and Currency Conversion

When a manual monetization had to be conducted, the co-benefit was directly calculated using a VSL adjusted to $_{2018}$USD. The currency adjustment for the VSL followed the same method as for other monetized values like for instance the carbon prices or total abatement cost estimates. The method is described using the monetized co-benefit values as an example in the following.

For cases where the monetization was already conducted, the currency was first adjusted for inflation applying a GDP deflation factor (DF) from the World Bank of the original currency using the equation below. The GDP implicit deflator is defined by the World Bank as "*the ratio of GDP in current local currency to GDP in constant local currency*" (World Bank, 2019). The base year varies by country and is for the US in 2010. To account for the different base years of the studies, the DF in 2018 had to be divided by the DF in the base year.

Equation 2: Currency deflation

$$COB_{2018} = COB_{by} * \sum_{2018}^{by} DF$$

With COB_{2018} as the co-benefit in 2018, COB_{by} the co-benefit in the base year, meaning the currency base year used for the initial monetization by the co-benefit studies and $DF_{by\text{-}2019}$ as the deflation factor for the period between the base year and the target year 2018.

In cases where a low and high range of co-benefits was provided by the studies, for instance from applying different stringent policies or changes in the baseline, also a low and high estimate for the VSL was applied. When the co-benefit was only given as a medium or average estimate, also just the medium VSL was applied. A list of the country-specific VSL (in million $_{2018}$USD) adapted for currency and extracted from Vandyck et al (2018) can be found in the table below.

Table 4: VSL values for manual monetization of co-benefits in 2030 (in million 2018USD) original values in brackets (in million 2005USD) (adjusted from Vandyck et al., 2018)

Country	**Low**	**Medium**	**High**
China	1.87 (1.5)	3.79 (3)	5.68 (4.5)
India	1.01 (0.8)	1.89 (1.5)	2.9 (2.3)

For the calculation of the country-specific VSLs, Vandyck et al (2018) used the VSL for the USA in 2005 as base value and adjusted it for the different regions by multiplying with the purchasing power parity. The VSL across regions (i) and time (t) was specified in relation to the real income per capita (*I*) in the following way:

Equation 3: Value of Statistical Life

$$VSL^{i}{}_{t} = VSL_{USA}^{2005} * \left(\frac{I^{i}{}_{t}}{I_{USA}^{2005}}\right)^{0.8}$$

Where (I^{i}_{t}) is defined as GDP per capita purchasing power parity with a price elasticity of 0.8 (West et al., 2013), which falls within the range (0.7-0.9) recommended by the OECD (OECD, 2012). The high and low VSL estimates for 2005 in the US are based on West et al. (2013) while the medium VSL represents an intermediate estimate (Vandyck et al., 2018; West et al., 2013). The VSL value in 2005 USD was converted via the above-described method to 2018 USD before they were used to monetized premature deaths.

3.1.2 Overview of the identified health co-benefit studies

All extracted and adjusted co-benefits were filled into a list including the author, covered sectors, reference scenario, mitigation scenario, country, co-benefit estimate including range, currency, assessment period, calculations applied in this thesis and notes.

Many papers offered a big range of individual values due to, for instance, different policy stringencies that have been explored, or other conditions applied to the assessment. The aggregated value for the health co-benefit from reduced air pollution is given as median with the 10^{th} and 90^{th} percentile as the range in brackets.

All identified studies including their key parameters have been summarized in Table 5 below. All co-benefit estimates are the result of climate mitigation measures in a specific sector like power or transport or are economy-wide estimates based on a lowered emission pathway compared to a reference scenario. In the table, these specifications can be found in the “Scenario” column. The values are based on many different assumptions taken by the authors with the most important ones mentioned in the table.

Some studies were excluded from this thesis and are not listed in Table 5 although they offered data since they either focused on assessment years, that were too different compared to 2030, as the case with Parry et al. which provided co-benefits in 2010 (Parry et al., 2015). For other studies mandatory data was lacking which would be required to calculate the desired unit of Dollar per ton CO_2 avoided. For instance, in some cases, a certain amount of reduced premature deaths was listed, but no indication of the amount of emission reduction responsible for the change was provided. The table below therefore only shows the studies that have been used for the assessment.

Table 5: Overview over the in this thesis analyzed co-benefit studies including their key parameters

Study	Reference Scenario	GHG mitigation scenario		Covered Sectors	Average co-benefit (low - high) [USD_{2018} /tCO_2]	Assessment year/ period	Applied harmonization (beside inflation adjustment)	Notes
		Name	Scenario variant					
China								
Vandyck et al. 2018	Current policy scenario	NDC (2.5 - 3.2°C warming)	Fixed	Economy-wide	161 (81 - 219)	2015 - 2050 (no year-specific values available)		Co-benefit values refer to the average in the period 2015-2050 and include health benefits from reduced air pollution as well as crop yield increases. Fixed air pollution policy
			Stringent		58 (51 - 122)			Stringent air pollution policy
			BAT		64 (23 - 135)			Best available technology (BAT) air pollution policy
		2°C (>75% chance to stay below 2°C by 2100)	Fixed		193 (84 - 309)			
			Stringent		133 (58 - 206)			
			BAT		97 (45 - 154)			
Li et al. 2018	BAU	3% Policy		Economy-wide	85	2030	Calculated monetized co-benefit per ton CO_2 avoided with data from paper ($/t CO_2 avoided)	Continuation of China's CO_2 reduction prior to 2015 Paris Agreement
		4% Policy			101	2030		The 4% Policy is consistent with China's recent commitment to halt its rise in CO_2 emissions by 2030
		5% Policy			113	2030		The 5% Policy reduces China's CO_2 intensity to the projected world average in 2030
Peng et al. 2018	GAINS ECLIPSE_ v5a_base emissions	ELE_LowC_ Trans		Transport, Power	99	2030	Calculated $/t CO2 avoided based on paper data; using monetized benefit and % reductions in emissions from paper compared to BAU (China CO_2 emissions GAINS ECLIPSE_v5a_CLE_ base as specified in the paper)	half decarbonized electricity sector (52% coal approx. 480g CO_2e per KWh + electrify 30% of road vehicles)
		ELE_LowC_ Resid		Residential, Power	94	2030		half decarbonized electricity sector (52% coal approx. 480g CO2e per KWh + electrify 30% coal-based heating and cooking stoves
		ELE_lowC_T rans&Resid		Transport and Residential, Power	121	2030		half decarbonized electricity sector (52% coal approx 480g CO_2e per KWh) + electrify 30% of road vehicles and 30% of coal-based heating and cooking stoves
IRENA, 2015	Reference	REMAP		Power	96 (37 - 155)	2030	Calculated monetized co-benefits per ton CO_2 avoided with data from paper ($/t CO_2 avoided))	using IRENA ReMAP options compared to REF as current policy scenario; net-incremental benefit in 2030
West et al., 2013	REF	RCP 4.5		Economy-wide	774 (387 – 1161)		Calculated monetized co-benefits per ton CO_2 avoided with	REF assuming an intermediate pathway for economic development and population growth, and assuming no climate policy.

Study	Reference Scenario	GHG mitigation scenario: Name	GHG mitigation scenario: Scenario variant	Covered Sectors	Average co-benefit (low - high) [USD2018 /tCO_2]	Assessment year/ period	Applied harmonization (beside inflation adjustment)	Notes
							data from paper ($/t CO_2 avoided)) and Medium VSL from Vandyck et al. (2018)	
Markandya et al., 2009	BAU	Limited trade		Economy-wide	7	2030		BAU: no additional measures to reduce GHG limited trade: 80% GHG reduction by developed countries by 2050 and the rest of the world what is necessary to achieve 50% reduction by 2050. Emission trading of developed countries, not for developing. full trade: 50% global reduction by 2050, cuts are only made wherever most cost-effective
		Full trade			8			
He et al. 2010	BAU	BAU + CCP		Economy-wide	16 (3 - 32)	2030	Calculated monetized co-benefits per ton CO_2 avoided with data from paper ($/t CO_2 avoided))	Medium, low, high VSL from Vandyck et al.; CCP: Industry, Building, Household, Vehicle efficiency improvements
		BAU + CCP + PCP			48 (8 - 93)	2030		PCP: Air pollution policies, vehicle standards
Study	**Reference Scenario**	**GHG mitigation scenario: Name**	**Scenario variant**	**Covered Sectors**	**Average co-benefit (low - high) [USD2018 /tCO_2]**	**Assessment year/ period**	**Applied harmonization (beside inflation adjustment)**	**Notes**
India								
Vandyck et al., 2018	Current policy scenario	NDC (2.5 - 3.2°C warming)	Fixed Stringent BAT	Economy-wide	290 (174 - 412) 206 (129 - 322) 167 (67 - 187)	2015-2050 (no year specific values available)		Co-benefit values refer to the average in the period 2015-2050 and include health benefits from reduced air pollution as well as crop yield increases
		2°C (>75% chance to stay below 2°C by 2100)	Fixed Stringent BAT		309 (142 - 390) 200 (138 - 294) 90 (45 - 142)			
IRENA, 2017	Reference	REMAP		Power	191 (64 - 317)	2030	Calculated monetized co-benefits per ton CO_2 avoided with data from paper ($/t CO_2 avoided))	using IRENA ReMAP options compared to REF as current policy scenario; net-incremental benefit in 2030
Peng et al. 2015	BAU - CLE	AMB	CLE	Power	46	2030	Calculated monetized co-benefits per ton CO_2 avoided with data from paper ($/t CO_2 avoided)) and	WEO: World Energy Outlook 2017, New Policy scenario AMB: NITI Aayog, Government of India, Draft Energy Policy 2017, Scenarios for 2022 and 2040CLE: Successful implementation of current legislation, especially the emission standards for coal power plants released in 2015
		WEO	CLE		128			
		WEO	DEL		87			

							Medium VSL from Vandyck et al. (2018)	DEL: 10-year delay in control strategy compared to CLE
Markandya et al., 2009	BAU	Limited trade		Economy-wide	57	2030		BAU: no additional measures to reduce GHG limited trade: 80% GHG reduction by developed countries by 2050 and the rest of the world what is necessary to achieve 50% reduction by 2050. Emission trading of developed countries, not for developing. full trade: 50% global reduction by 2050, cuts are only made wherever most cost-effective
		Full trade			53			

3.2 Step 2: Quantification of Emission and Cost Pathways

To estimate the potential impact of co-benefits on the cost development of a certain emission scenario, the cost curve for a certain scenario had to be developed. IAMs however usually do not illustrate the marginal abatement cost curve of a specific year, since the mitigation costs are usually the sum of many different model runs with varying strictness on the CO_2 limits (Kesicki, 2011).

The estimation of the MACC relied on IAM data and as such resembles the shape of a model derived MACCs discussed in section 2.2.2.2 and displayed in Figure 4b.

Different data points provided by the database have been tested to estimate a MACC in 2030. The tests finalized in a method requiring three types of input data from the database. The total emission abatement of the reference and mitigation scenario in 2030 in Mt of CO_2 and the carbon price ($/t CO_2) used to achieve the abatement in the mitigation scenario. A third input value extracted from the database was a measure on the total mitigation costs which in the database was referred to as “total Policy Costs”. This indicator was deduced from the area under the MACC in billion USD. How these values have been used to estimate the MACC is described in the following section.

The ADVANCE project compared multiple scenarios ranging from different temperature goals to different levels of ambition (IIASA, 2019). To make the two IAMs comparable, they had to run the same scenario with the same basic assumptions. Some of the scenarios explored delayed action starting in 2030 which fell out of the assessment period of this thesis leaving only the scenarios exploring mitigation action starting in 2020. Of the three early action scenarios with action starting in 2020, one pathway was selected which would achieve 1.5˚C by 2100 with a chance above 67 percent. The specifications and limitations of the scenario were summarized in the table below.

Table 6: Scenario specifications (IIASA, 2019)

Scenario	**Temperature Target**	**Emission Budget [cumulative 2011-2100]**	**Chance to stay below target**
2020_2100_1.5C	1.5°C	400 $GtCO_2$	>67%

The above-described data points were extracted from the project database and processed (IIASA, 2019). The emission data was converted to $GtCO_2$ and the carbon prices in $/$tCO_2$ were adjusted for inflation and converted to $_{2018}$USD to ensure uniformity of all cost estimates.

The table below shows an overview of all the input data extracted from the IAM database which was required for the estimation of the cost curve in the following section.

Table 7: Overview of input data from the IAM database

			Emission Gap (Gt CO_2)	Carbon Price ($_{2018}$USD/tCO_2)	Total Abatement Cost (billion $_{2018}$USD)
China	IMAGE 3.0	1.5°C	5.2	525	675
	POLES ADVANCE		9.6	227	606
India	IMAGE 3.0	1.5°C	1.6	522	283
	POLES ADVANCE		1.8	228	117

As Table 7 shows, the carbon price in 2030 differs significantly between the two IAMs. This difference is due to the assumptions taken by the model developers.

While the carbon prices differ for each region between the two IAMs, they are very similar within each IAM between the two regions. The reason for that observation could be, that the carbon price is, as explained in section 2.2, the result of global optimization. The country-specific carbon prices are therefore just an approximation based on assumptions from this global average. The assumptions for China and India, therefore, seem to result in similar carbon prices.

Showing the carbon price for only the year of 2030 does not give much information on how the different models arrive at the estimate. It is further important to see how the carbon price develops over the full assessment period. Illustrating for instance the carbon prices applied from both models across the assessment period for the 1.5°C scenario in India results in the curves depicted in the figure below. The same development can be seen in China.

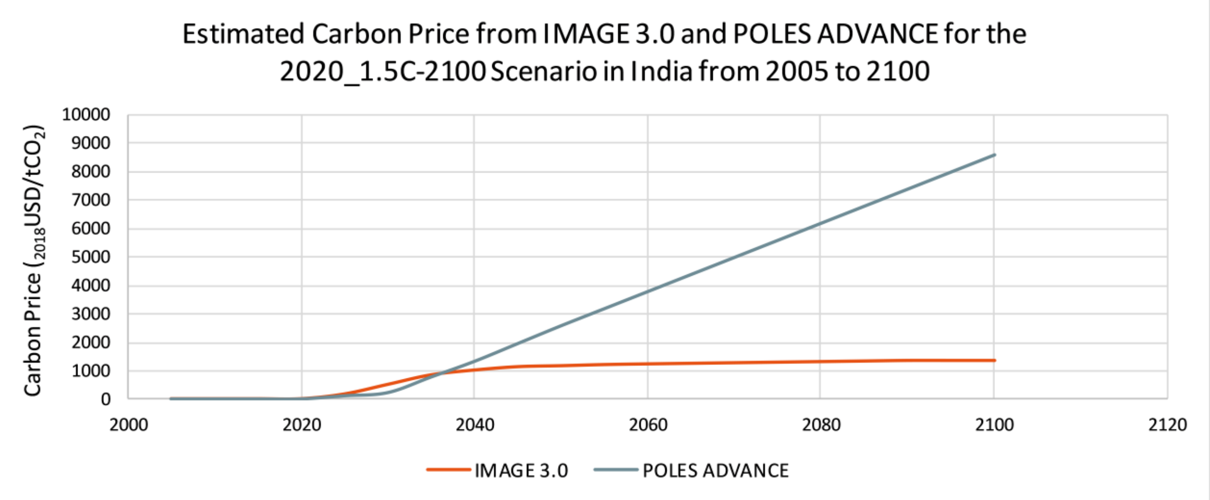

Figure 8: Comparison of Carbon Price from IMAGE and POLES over the full assessment period for the 1.5°C scenario in China

This comparison shows, that the applied carbon price from POLES in 2030 is lower than the carbon price for IMAGE. After 2030 however, the development of the carbon price in both models is different. While the carbon prices only slightly increase until 2030 for IMAGE and almost stagnates towards 2100, the carbon prices from POLES increase at a fixed rate until the end of the assessment period. At the end of the assessment period, the carbon prices from POLES are almost six times higher than those from IMAGE.

The impact the different cost estimates of the models have on the emissions levels at net-zero costs will be shown in the results (section 4).

3.2.1 Step 2.1: Estimating the Marginal Abatement Cost Curve Without Co-Benefits in 2030

Step 1 (section 3.1) of the research described which data points were extracted from the IAM database. This section describes how the extracted data was applied to estimate a MACC in 2030.

As the MACC originates at zero abatement and zero costs (P1) and the endpoint of the curve is located at the total abatement of the scenario and the corresponding carbon price (P2), a curve between the points is straight. This does however not accurately represent the total abatement cost referred to as the area under MACC indicator in the IAM database. To ensure that the MACCs accounts for the total mitigation costs provided by the IAM database, the curve had to be transformed so that its shape results in the shape, of which the area under that curve is equal to the pre-requisite (A). The relation of the different parameters has been illustrated in the exemplary figure below.

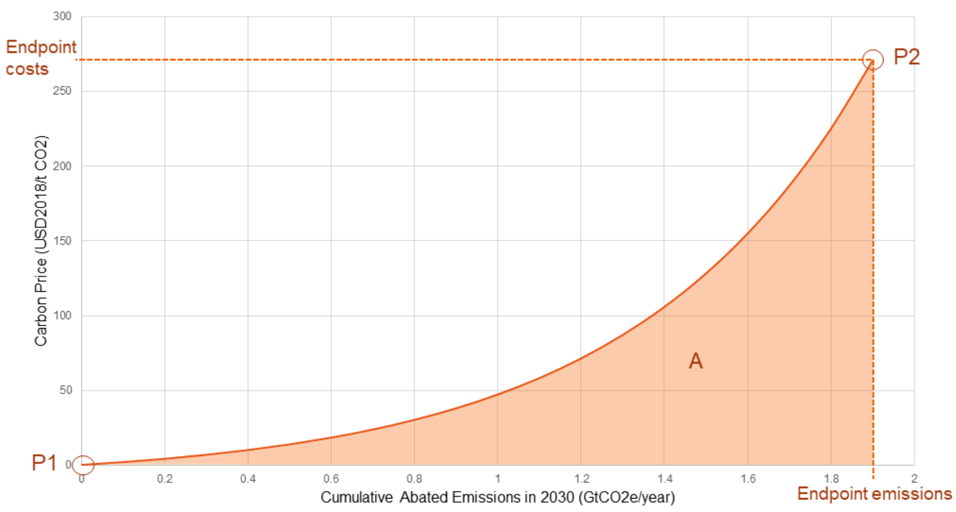

Figure 9: Relation of input parameters on estimated MACC

There are different types of functions, that could potentially represent the shape of a MACC. When calculating the integral of the straight line between the two points, the resulting area was bigger than the pre-requisite. This means that the function had to be convex towards the x-axis, therefore reducing the area compared to the integral of the straight line.

As defined in 2.2.2, model-derived MACCs always have to start at zero costs for zero emissions. A logarithmic function does not allow to go through the origin and can therefore not be used for the assessment. A 2-degree polynomial function was able to meet most of the requirements and was also able to produce feasible MACCs for some of the scenarios. For others, however, the function resulted in negative values or a “bloating” of the curve for some input parameters and does therefore also not accurately represent a model derived MACC. Leaving a power function and an exponential function as base to estimate the MACC equivalent.

The exponential function has multiple benefits over the other functions. An exponential function is always convex and can start at zero. A “bloating” as experienced with the polynomial function could not occur. Instead, the function resulted in an error for these types of input parameters leading to the exclusion of those data combinations. The exponential function was able to display the input parameters the best and was selected for the assessment.

As one condition for the curve was to originate at the origin (P1 in Figure 9) the general expression of the exponential function () was adjusted to meet this requirement. To ensure that the curve originates in zero, parameter “c” in Equation 4 had to be adjusted so the condition was met. This was achieved by substituting 0 for “x” and “y” in Equation 4 and solving for “c” resulting in “c” being equal to “-a”, illustrated in Equation 5.

Equation 4

$$f(x) = y = a * b^x + c$$

Equation 5

$$c = -a$$

"c" is now set to allow the curve to go through the origin. Substituting the new "c" (Equation 5) in for "c" in Equation 4 results in the new expression of the exponential function that meets the earlier stated requirement and is depicted in Equation 6.

Equation 6

$$f(x) = y = a * b^x - a$$

Since the curve is not only dependent on two points but should also account for the area under the curve represented by the area under the MACC variable from the IAM database, the integral of Equation 6 was created, represented in Equation 7.

Equation 7

$$\int f(x)dx = F(x) = A = a * (\frac{b^x}{\ln(b)} - x)$$

Solving both Equation 6 and Equation 7 for the parameters "a" and "b" results in the following equations representing the two parameters.

$$a = \frac{y - A * \log b}{x * \log b - 1}$$ Equation 8

$$b = \sqrt[x]{\frac{a+y}{a}}$$ Equation 9

Where parameter "y" is the carbon price, "A" the total abatement costs, "b" as the second parameter in Equation 10 and "x" as the emission abatement. Both "x" and "y" refer to the total abatement and final carbon price for 2030 provided by the database.

Since the parameters "a" and "b" are both depending on each other, the parameters cannot simply be calculated. Instead, the actual values of the parameters have to be approximated by numerical approximation.

The approximation follows multiple conditions. First, Equation 6 and 7 have been written down depending on the two parameters "a" and "b", however, some hardcoded values were substituted in for the function of the two parameters. One condition was that the integral function (Equation 7) had to be equal to the pre-requisite value from the database. Solving for these conditions resulted in the parameters "a" and "b" which change for every change in the input variables country, IAM and scenario.

The parameters are responsible for influencing the shape of the curve. Substituting both the approximated parameters in Equation 6 results in the corresponding values for the carbon price. And when substituted in the integral function in Equation 7, "A" resulted in the prerequisite total abatement cost. When having rows of successively increasing x-values, representing the emission abatement, up to the maximum abatement per scenario, the function with the parameters results in the corresponding carbon prices for each step in abatement, arriving at the function which is true to the input values and conditions.

An additional benefit of the chosen method is, that there is only one solution for the curve with the given information. The characteristics of the exponential function as well as the combination of the area under the curve between and that the function is only viewed between zero and the total abatement leaving only one possible shape for the curve open. In terms of the shape of the MACC, no sensitivity analysis is required with the provided data.

3.3 Step 3: Estimating the marginal abatement cost curve with co-benefits in 2030

Since the marginal abatement cost curve was created based on model-derived mitigation costs by an integrated assessment model, there was no specific information on mitigation measures available. The abatement potential of specific measures is therefore not visible in the curve, but instead, the curve displays the cost of a package of measures in the form of carbon prices. It was therefore not possible to allocate the co-benefits to certain measures, or certain abatement, more than to others.

To allow for such an allocation, the change in the fuel composition of the mitigation scenario could have been compared to the reference and fuel-specific co-benefit estimates could have been applied. Due to the mentioned difficulty in attributing a value to the co-benefit alone in a country in a specific year, it is even harder to attribute a monetized co-benefits to a specific fuel. Due to that, data for fuel-specific co-benefits is very limited. Additionally, the fuel-specific emission data from the IAM database was incomplete so that this step was not conducted for this assessment.

To simulate however the characteristic that different fuels have different amounts of co-benefits associated with their removal, three different types of distributing the co-benefit over the curve have been applied. When no information on the allocation of different technologies across the cost curve is given, the fairest option to allocate the co-benefits is equally along the cost curve as equal distribution.

As a second approach, a “Max-Min distribution” of the co-benefit was applied as well, which assumes that the low-cost options of the curve result in a bigger co-benefit than the higher-cost options. This is based on the idea that the highly polluting fossil fuels that are getting replaced are generally located on the low-cost part of the curve, where more efficient fossil power generation is located on the higher cost end. The power generation with coal, for instance, results in a much higher amount of health impairing air pollutants compared to other fossil fuels like natural gas (Jenner and Lamadrid, 2013). Additionally, the air pollutants released by coal are considered to have a greater negative impact on health than those released by burning natural gas (Nicoletti et al., 2015). This distribution represents an extreme case and assumed double the selected co-benefit category at the start and zero benefits for the last abated emission on the curve. Lastly, a more intermediate case was assumed where the benefit does not fall to zero for the last abated emissions but rather reduces to half of the base co-benefit category applied for the first abated emission. The curve, therefore, ends between the Max-Min distribution and the equal distribution and is called “50%” distribution.

An overview of all investigated cases is illustrated in the table below.

Table 8: Overview of investigated cases

		Co-benefit category		
Distribution	**Description**	**10th percentile**	**Median**	**90th percentile**
Equal	Base co-benefit equally subtracted from each marginal increase in emission reduction	Estimated for China and India, IMAGE 3.0 and POLES ADVANCE for the 1.5˚C pathway		
Max_Min	Subtracted co-benefit successively reducing to zero for the last abated emission			
50%	Subtracted co-benefit successively reducing to 50% of the base co-benefit			

All combinations together resulted in 36 different analyzed cases.

The equal distribution of the co-benefit category means that every marginal increase in emission abatement has its costs reduced by the same amount of co-benefit equal to the applied co-benefit category. This results in an equal downward shift of the curve but keeping the same shape as the estimated MACC. This downward shift is illustrated in Figure 10 below.

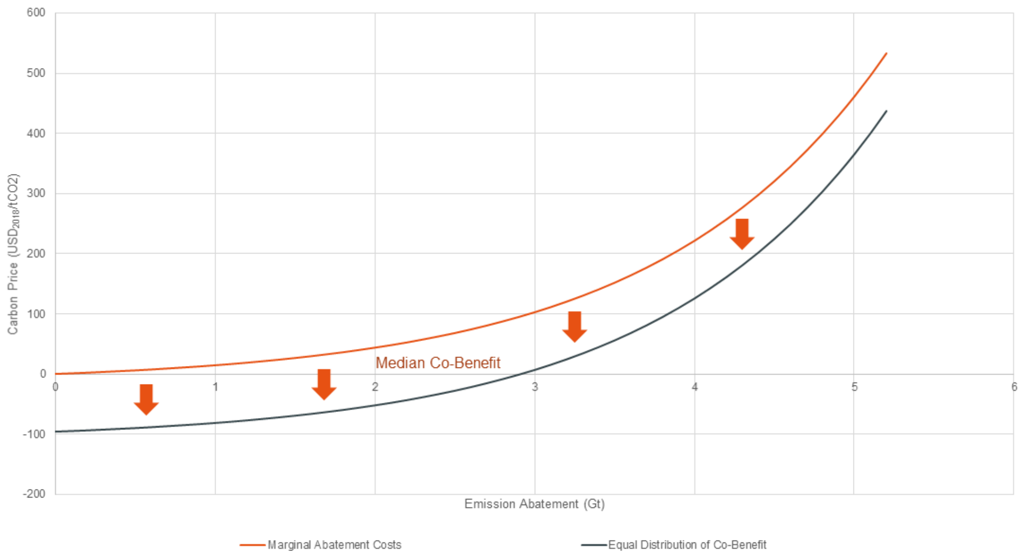

Figure 10: Illustration of an equally distributed median co-benefit

To make the three distribution types comparable, the values, they were based on, had to be constant. The area under the cost curve of the selected base benefit, representing the total co-benefit over the whole curve, had to be the same for all distribution types. The total co-benefit was calculated by applying Equation 8.

Equation 8

$$COBtotal = COBcat * total\ abated\ emissions$$

Where “*COBtotal*” is the total co-benefit which is equal to the area between the old and the new shifted MACC and “*COBcat*” the selected base co-benefit value from one of the three co-benefit categories.

For the equal distribution, the area function resembles a rectangle. For the Max-Min distribution, however, the distribution of the total co-benefit rather had the form of a triangle. Taking one of the in Step 1 (section 3.1) calculated “base benefits” for the Max-Min distribution, one needed to assume double the base benefit for the first mitigation cost value to arrive at zero benefits for the last mitigation cost value on the curve following a linear distribution. To arrive at the value that had to be subtracted from the cost curve, for each consecutive step of abatement one had to divide double the amount of the base co-benefit by the number of individual steps equal to the number of abatement values for the curve illustrated in the equation below. The value the mitigation costs get reduced by for each marginal increase in abatement will be called “*Subtractor*” in the following.

Starting with double the amount of base co-benefit for the first abatement value, the amount subtracted from that for the second step in abatement, was then the previous amount minus the subtractor resulting in zero for the last abatement value to be subtracted. The Subtractor can also be described as the difference in carbon price between each marginal increase in emission abatement (see Figure 10).

Equation 9

$$SubtractorMin\_Max = \frac{2*COBcat}{\sum steps\ in\ emission\ reductions}$$

With “*SubtractorMin*_Max” being the value that gets subtracted from the previous value for the mitigation costs and “*COBcat*” as the selected co-benefit category value.

Where the area of the total co-benefit for the Max-Min distribution resembles a triangle, the area for the 50% distribution resembles the shape of a trapezoid. The point which was known for this distribution was the value for the mitigation costs at the last point of emission abatement since it had to be 50% of the COBcat. The starting point for the mitigation costs after the inclusion of co-benefits was then calculated by reforming the area function of a trapezoid illustrated in the equation below.

Equation 10

$$StartY = \frac{2*COB_{total}}{total\ emission\ gap/y} - \frac{COBcat}{2}$$

With “StartY” being the mitigation costs of the adjusted curve for the first unit of abatement, “*COBtotal*” being the total co-benefit and “COBcat” as the selected co-benefit category.

The subtractor value for the 50% distribution was then calculated by applying Equation 11.

Equation 11

$$Subtractor50\% = \frac{StartY - total\ emission\ gap/y}{\sum steps\ in\ emission\ reductions}$$

Where “StartY” is the mitigation costs of the adjusted curve for the first unit of abatement.

An illustration of both un-equal distribution types can be found in the figure below. It further illustrates the points that had to be estimated for the two different distributions and how the different parameters of the equations relate to each other.

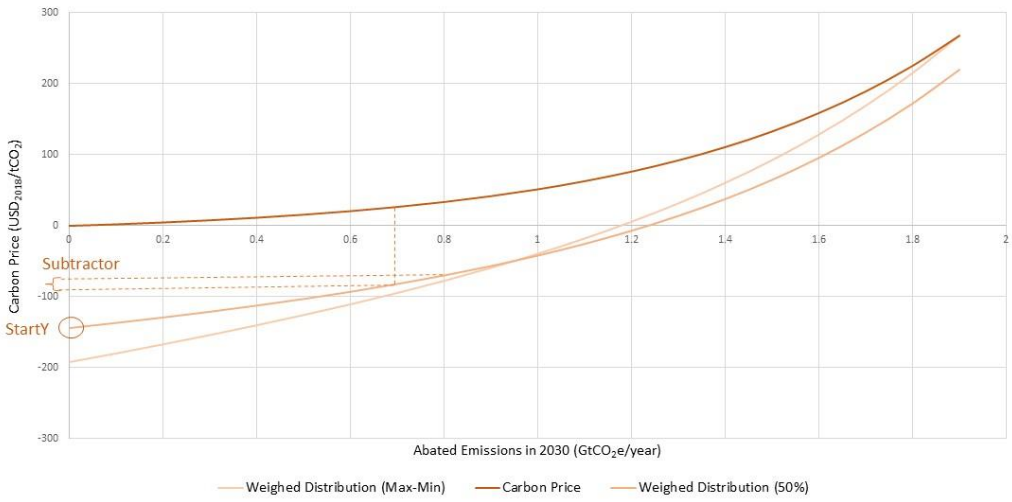

Figure 11: Exemplary illustration of the two un-equal distribution types

To see the difference between the three ways of distributing the co-benefits, all options were compared in a graph.

3.4 Step 4: Estimation of the emission levels at net-zero cost

The emission levels at net-zero costs are defined as the amount of GHG abatement possible for negative or zero costs after the inclusion of co-benefits. This is equal to the amount of emission abatement, where the shifted MACC intersects with a carbon price of zero as illustrated in Figure 12 below. Since all model-derived MACCs start at zero costs for zero abatements, the emission level at net-zero costs is always the point where the new cost curve including co-benefits changes to positive carbon prices. The point of intersection can be found by finding the cross point of the function MACC including co-benefits. Since the type of function is a downward shifted exponential function, the curve has only one point where the mitigation costs are equal to zero, meaning there is only one solution to the function.

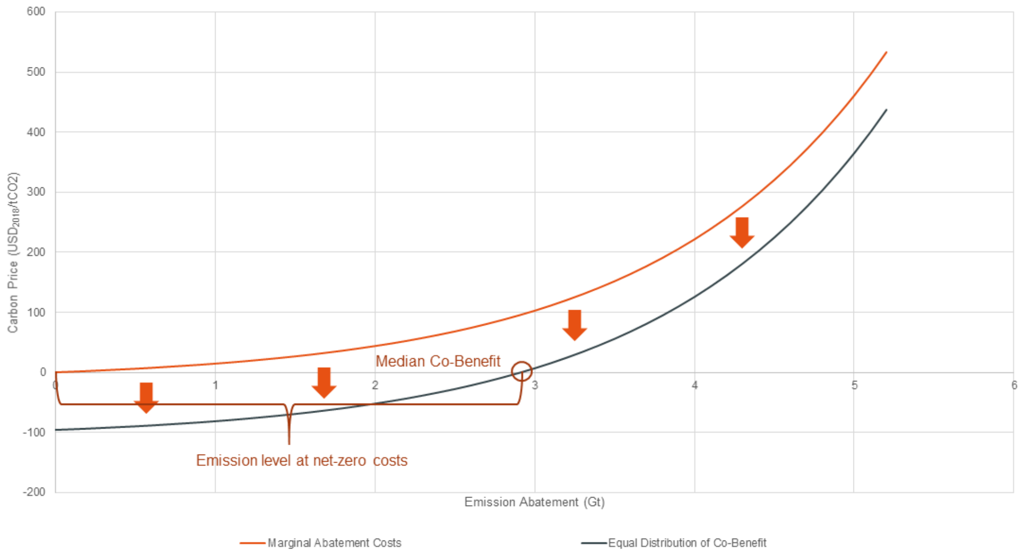

Figure 12: Illustration of the location of the net-zero mitigation potential on the adjusted MACC

The emission levels at net-zero costs were calculated by finding zero crossings of Equation 6 including co-benefits. However, depending on the type of distribution and the selected co-benefit base value, the function of the shifted curve changes as illustrated in Figure 11 in the previous section.

Equation 7 was therefore adjusted for the distribution types. The Max-Min distribution follows Equation 12 depicted below.

Equation 12

$$f(x) = ab^x - a - \frac{2 * COBbase - x}{SubtractorMax\_Min}$$

Where "*a*" and "*b*" are the in Step 3 estimated parameters, "*x*" the emission abatement, "*COBbcat*" the selected co-benefit category, and "*Subtractor_Min_Max*" the in Equation 9 depicted subtractor value.

The 50% distribution required a different adjustment to Equation 6 illustrated in Equation 13 below.

Equation 13

$$f(x) = ab^x - a - \frac{StartY - x}{0.1 * Subtractor50\%}$$

Where "*StartY*" is the in Equation 10 calculated start value for the mitigation costs including co-benefits and "Subtractor50%" the in Equation 11 calculated amount of reduction from the previous mitigation cost value for each marginal increase in abatement.

The resulting value for "x" is the emission abatement of the scenario in 2030. Solving for "x" where f(x) equals zero, results in the point of intersection and with that in the amount of mitigation at net-zero costs. Since this assessment compares several different input parameters, like the applied co-benefit, the region and/or the IAM, there are many different outputs that can occur based on the combination of those variables.

When shifting the cost curve down by including the health co-benefits, the mitigation costs for the mitigation scenario have been reduced. This reduction in costs was however not displayed in monetary terms, but rather shown in the emission levels possible at net-zero costs when accounting for health co-benefits. Since model derived cost-curves assume the cost for any given amount of abatement, a downward shift of the MACC results in all emissions up to the point where the curve a carbon price of zero, to count towards the emission level at net-zero costs. It is, however, important to note, that this is not displayed as an additional potential on top of the mitigation scenarios, but rather shows the part of the costs reduction from considering co-benefits as the amount of emissions abatement possible, with the new "no-regret" options from considering co-benefits. It is just a different way of illustrating the positive impact from co-benefits of climate mitigation. This identified emission level at net-zero costs can then also be illustrated as a share of the emission gap in 2030 achievable for net-zero costs.

3.4.1 Estimation of the cost reduction from health co-benefits

To make the relation of co-benefit and costs even clearer, the costs of the mitigation scenario including and excluding the co-benefits are shown as well. The total costs of the scenario per year are given as the total mitigation costs in billion $_{2018}$USD provided by the IAM database. The cost reduction from the co-benefit is calculated as the reduction of the area under the curve since the area under the curve was used as an indicator, provided by the IAM database, for the total abatement costs.

To calculate the area under the MACC after the inclusion of the co-benefit, the area function represented in Equation 7. in section 3.2.1, was adjusted. The inclusion of the co-benefit shifts the whole MACC down by the amount of the co-benefit when the benefit is applied with equal distribution. The adjusted area function for the equally distributed co-benefit can be found in Equation 14 below.

Equation 14

$$\int_{x_{net_{zero}}}^{x_{total}} f(x)dx = F(x) = A = \frac{a * b^x}{\ln(b)} - x * (cob + x)$$

Where "x_total" and "x_net_zero" are the two boundaries of the defined integral. The upper boundary, "x_total" is the total abatement in 2030 for the specific case, and the lower boundary is the net-zero emission level ("x_net_zero") for the specific case. The parameters "a" and "b" are the per numerical approximation calculated parameters of Section 3.1.2.1, and the "x" gets substituted by the two boundaries when calculating the integral.

The case-specific calculation results in the area under the curve of the shifted co-benefit function. The difference between the area under the curve of the estimated MACC and the area of the co-benefit curve as a percentage gives the percentage reduction of the total abatement cost by the health co-benefit.

Only in cases where the identified emission level is greater than the emission gap in 2030, the upper and lower boundary has to be switched. The value will be negative, as it will represent the additional amount after the generated MACC and between the co-benefit curve. The percentage cost reduction in these cases will be above 100%.

3.5 Limitations of the Method

3.5.1 Co-Benefits

The median co-benefit used for the assessment was generated based on different co-benefit estimates extracted from the literature. As described in the theoretical background, co-benefits are highly case-specific making them hard to compare even when converted to the same units. The co-benefits extracted from the literature generally followed similar major assumptions on, for instance, the mitigation scenario or the region. Some detailed assumptions, however, differ between the extracted benefits. These include for instance the health response functions or the VSL that was applied.

The co-benefit used for the assessment is the median of all studies or the 10th and 90th percentile estimates. An increase in data points was valued higher as it gives a better indication of the "middle" co-benefit discussed in the literature for the specified region in 2030. Applying an average co-benefit estimate on the data points would have resulted in much higher co-benefit averages due to very high co-benefit estimates from especially West et al. (2013). The Median, therefore, gives a much more nuanced view of the co-benefits, which is represented by the majority of studies.

The co-benefit values extracted from the literature are all highly aggregated. The actual health co-benefits are depending on many parameters. Besides the local circumstances for instance, also the stringency of the policy or how well the policies got implemented is a deciding factor on the number of achievable co-benefits as it has an impact on how much emissions are abated (Vandyck et al., 2018).

Additionally, the extracted co-benefits were most of the time resulting from climate action in line with keeping the temperature rise below 2°C. In this assessment, these co-benefits were, however, due to the latest reports by the IPCC, applied to a 1.5°C pathway. The co-benefits in this method are not a result of the different emission reductions, which the models estimated but are rather applied ex-post. This could lead to inaccuracies. The accuracy could, however, be increased by applying specifically extracted co-benefit values which were calculated based on a similar amount of emission reduction as the scenario they have been applied to in this thesis. The number of co-benefit estimates on 1.5°C scenarios, however, was limited. Due to a lack of data, the co-benefits resulting from different temperature targets were aggregated in this thesis.

3.5.2 Estimated MACC

The estimation of the MACC in Step 2.1 (section 3.2.1) of the research required input data from the IAM database. Of those data points, the carbon prices were consistent with the emission abatement. The total abatement costs, however, did not seem to correlate with the carbon prices and the mitigation gap. While theoretically, the area under the MACC can represent the total abatement cost in the target year in a simple representation (Paltsev and Capros, 2013), it is most likely not accurate with the MACCs used by the analyzed models. As described earlier, the carbon price estimated by the model is an equilibrium carbon price, resulting from demand and supply curves which were generated from different regional MACCs (PBL, 2014). The policy cost measure from the database given as "area under MACC" (AUM) could, therefore, not refer to a single MACC but rather be a middle estimates of multiple estimated MACCs and not directly correlate with the carbon prices estimated in the model, as it has been assumed for this thesis.

Additionally, the regional MACCs used in the IAM are an input in the model itself, while the policy costs in the target year are described as a final model output. Many different parameters besides the economic estimation using MACCs, are used to estimate the total abatement costs (PBL, 2014). Despite the model calling this parameter “Area under MACC” it may not solely refer to this area but also include other processes in the model resulting in the value.

The assumptions and limitations led to the exclusion of whole regions due to inapplicability with the applied method. An assessment for Europe was, for instance, conducted and data gathered. However, since the AUM provided by the database was bigger than the integral of the carbon price for Europe, the resulting cost curve would have been “bloated” and due to that, not possible to be displayed as an exponential function.

3.5.3 Emission Levels at Net-zero Costs

The net-zero cost emission reduction potential from the identified health co-benefits in China and India is the main result of this thesis. As one of the final outputs, it is limited by most of the previously mentioned limitations as well.

The choice of the three input parameters for the estimation of the MACC in 2030 was based on testing multiple ways of generating a MACC using openly available IAM data. With this amount of limited input data, each of these has a great influence on the final output. The most influential parameters are the carbon price especially in combination with the total abatement estimated by the IAMs in 2030. These two parameters are the endpoint of the generated marginal abatement cost curve.

Since the general shape of the curve is always the same due to the choice of an exponential function and the same identified co-benefit is applied to both IAMs, the endpoint of the curve has a significant impact on the emission levels at net-zero costs. Essentially, the smaller the carbon price, the higher will be the emission level. Depending on the co-benefit, a larger part of the co-benefit curve is drafted below a carbon price of zero and therefore increasing the emission level at net-zero costs. Is the identified co-benefit greater than the carbon price and the distribution type is not the Max_Min distribution type, the method could result in an emission level greater than the total mitigation gap in 2030 suggesting an overachievement of the gap or in turn, that the co-benefits would be greater than the required mitigation costs.

The carbon price is therefore highly important in interpreting the results. Since the carbon price is however generated by integrated assessment models, the interpretation of the carbon prices is difficult due to the sophisticated nature of the IAMs as explained in section 2.2. It is therefore also difficult to interpret the emission levels at net-zero costs, given this dependence on the provided carbon price.

4 Results and Discussion

4.1 Identified Health Co-Benefits

The identified median health co-benefit for China is 96 (8 – 295) USD/tCO_2.The co-benefit estimates for China are based on 19 individual datapoints from 7 different co-benefit studies. For India, the Median estimate is 86 (54 – 369) USD/tCO_2 and based on 13 data points from 4 individual studies. Some studied provided data for both countries.

In contrast to the median estimate with the 10th and 90th percentile range applied in this thesis, the average estimates with the minimum and maximum range, further illustrate the characteristics of the dataset. The following numbers show the average health benefit with the minimum and maximum values as the range in brackets. For China, the average health benefit was estimated to be 177 (3 – 788) USD/tCO_2. In India, the average benefit is 101 (11 – 417) USD/tCO_2 and with that slightly lower than for

China with also lower maximum values. These numbers further illustrate, how a few studies with extremely high co-benefit estimates push the average significantly higher compared to the median.

There are however a few aspects of co-benefits that could be discussed in the context they are used for in this thesis.

The co-benefits in this thesis are used as a means to increase ambition from policymakers to act on climate change. The significance monetized co-benefits could have on influencing policymakers is however debatable. When displaying the co-benefits as reduced costs, the resulting message could be inaccurate since the co-benefits do not actually reduce the initial demand for investment cost for the mitigation. The co-benefits are when considered as cost reductions, a result of the successful implementation of the measures and trickle-down after their implementation. The initial burden of investment is not impacted by them. The cost reduction rather occurs, compared to not investing in mitigation options.

Furthermore, it is not clear which actors are benefitting from the monetized co-benefits. In physical terms, the people benefitting are the, in the case of health benefits, parts of the society which would be affected by the air pollution and the ones that would need to pay the burden of the health costs connected to the pollution which would be avoided via the health benefit. In addition to that, the discrepancy between the investors and beneficiaries in the climate change discourse mentioned in the introduction to this thesis is also true for the co-benefits. The co-benefits from reduced air pollution are following from the measures which were responsible for the reduction in air pollutants. While the governments can be the initiators for mitigation measures like solar or wind projects via climate policies, they are however not necessarily the investors of these measures and do therefore not carry the total abatement costs.

Estimating co-benefits on a more localized level could make it easier to estimate the co-benefits more accurately and to better identify the actors carrying the financial burden and the ones benefitting from the investment. Another dimension of this is the option to separate the assessment of co-cost. As most of the analyzed co-benefit studies showed, was the concept of co-cost not discussed in detail or excluded from the assessment, as it has been done in this thesis. Without estimating co-cost, co-benefits could have a substantial impact on reducing the cost of climate change. This isolated look on the benefits of climate action leads to a positive bias which could be resolved by estimating potential co-cost as well.

Multiple benefits and costs have to be considered in the decision-making in a systematic approach to increasing their impact (Ürge-Vorsatz et al., 2016). However, already a big range of estimates for just the co-benefits for health was identified. Including multiple potential co-benefits as it is advised by researchers (Ürge-Vorsatz et al., 2014), could be difficult to achieve. A few reasons for that have been explored in section 2.1. When estimating countrywide co-benefits their impact could be perceived positive and negative, for instance, for different sectors of the full economy. Translating different co-benefits to one cost measure could additionally prove difficult or may only be possible on very aggregated units like percentage of GDP across the whole country for a few co-benefit categories which could reduce their impact due to the increase in uncertainties (McCollum et al., 2013). The role co-benefits could take in the context of climate policy discourse is still being discussed. Due to their heterogeneity and limitations, using them in the climate policy discourse as a measure to reduce climate mitigation costs could be difficult (Nemet et al., 2010). Not trying to monetize the co-benefits and only using physical measures to emphasize the benefit of climate mitigation could potentially have a bigger impact on the policy discourse (Nemet et al., 2010; Ürge-Vorsatz et al., 2014). Showing the margin of cost reduction from the consideration of co-benefits in terms of emission levels could be an intermediate step that combines the monetized benefit with their physical impact.

4.2 Results Assessment

The results are compared between the two IAMs for China and India respectively. The comparison of figures focuses on the 1.5°C scenario as this is the goal set out by the latest reports from the IPCC (IPCC, 2018b). The emission levels at net-zero costs from the co-benefits are compared for each country between the different co-benefit categories and IAMs in a table at the end of this section.

4.2.1 Marginal Abatement Cost Curve in 2030

The cost curve for China was estimated based on the input data and the approach discussed in the Methods. IMAGE 3.0 estimates an emission abatement of 5.18 $GtCO_2$/yr for the 1.5°C scenario achieved by a carbon price of 526 USD/tCO_2 in 2030. With the assumed exponential trend of the cost development and total abatement costs from the IAM amounting to 675 billion USD in 2030 the cost curve (orange) shown in Figure 13 was drawn. Figure 13 shows in grey the estimated cost curve for China using the data from POLES. POLES assumes much more abatement for China in 2030 with 9.6 $GtCO_2$/yr and with that more than 4 $GtCO_2$ more than IMAGE. The carbon prices with which this abatement can be achieved are however with 226 USD/tCO_2 less than half the carbon price assumed by IMAGE. The abatement costs for China are estimated to be 606 billion USD in POLES for the 1.5°C scenario (grey).

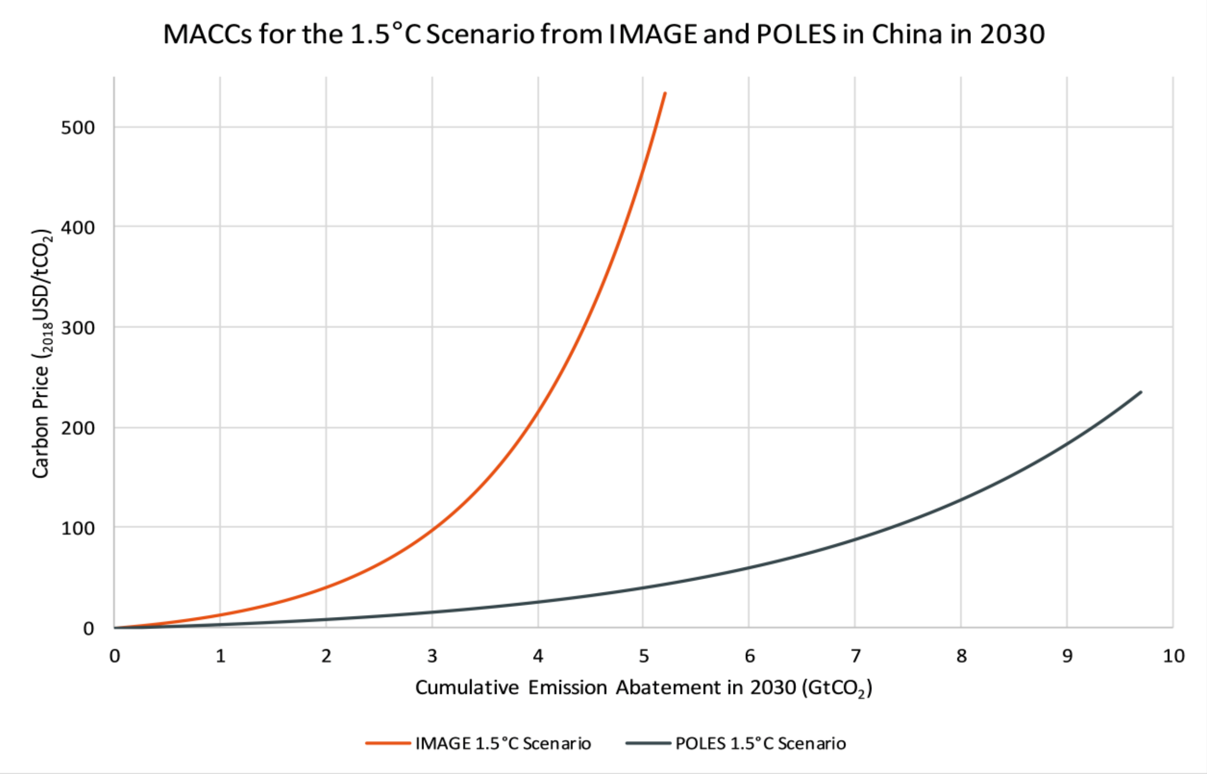

Figure 13: Comparison of the estimated MACC for China in 2030 for the 1.5°C scenario in IMAGE3.0 and POLES ADVANCE

The estimated MACC from IMAGE for China shows, that about 3 $GtCO_2$, so, more than 50% of the total abatement in 2030, can be achieved for a carbon price below 100 USD/tCO_2. In POLES, on the other hand, about 7Gt CO_2 of the total 9.6Gt CO_2, so about 70% of the total abatement can be achieved with such a carbon price.

The costs in both curves are progressively increasing towards the final steps of the emission abatement, illustrating the increased difficulty in reaching the “high hanging fruits” or harder to substitute parts of the abatement.

The difference between the two estimated MACCs for IMAGE and POLES can be explained by the different carbon prices and mitigation of both IAMs estimate for 2030. POLES assumes much more abatement for a much lower carbon price than IMAGE. As explained in section 2.2, the carbon price and the corresponding emission abatement estimated by the IAMs greatly depends on the assumptions taken by the developers of the models. The lower carbon prices in POLES in 2030, therefore, imply, that the model assumes a higher abatement potential for the lower mitigation cost options applied than it is the case for POLES.

For India, IMAGE estimates a total emission abatement for the 1.5°C scenario in 2030 of 1.6 $GtCO_2$/yr for a carbon price of 521 USD/tCO_2. The total abatement costs estimated by IMAGE amount to 674 billion USD. POLES estimates a total abatement in 2030 of 1.8 $GtCO_2$/yr with a carbon price of 228 USD/tCO_2 which is more than half the carbon price estimated by IMAGE. This difference in carbon prices results in a total assumed abatement cost in POLES that is with 116 billion USD also less than half the amount estimated by IMAGE.

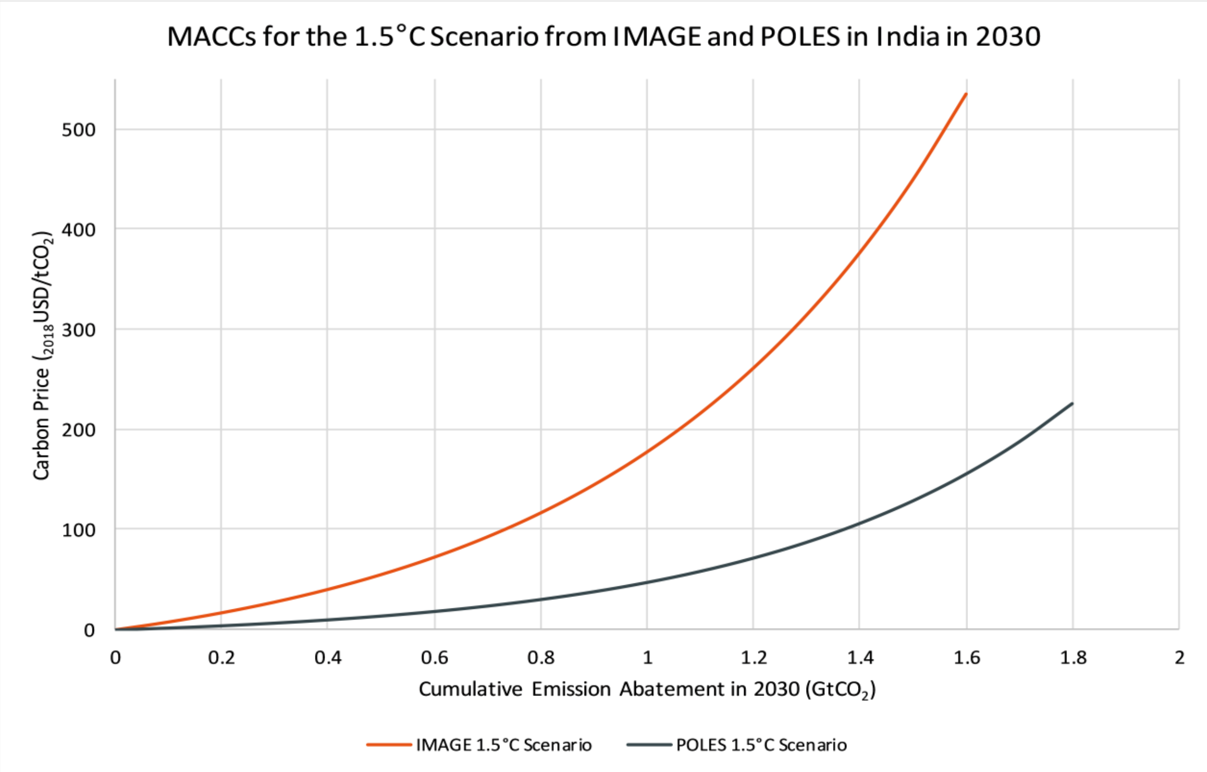

Figure 14: Comparison of the estimated MACC for India in 2030 for the 1.5°C scenario in IMAGE3.0 and POLES ADVANCE

Compared to the cost curve for IMAGE, the average carbon price in POLES is lower. The same level of emission abatement requires in POLES a lower carbon price than in IMAGE. Compared to the curves for China however, the total abated emissions in 2030 are similar in both models. Just the carbon prices are higher in IMAGE, resulting in about double the total abatement costs in IMAGE compared to POLES.

The reason why the carbon prices in 2030 are lower for POLES than for IMAGE is, as explained before, due to the different assumptions applied in both IAMs.

4.2.2 Impact of Co-Benefits on the Marginal Abatement Cost Curve

The potential impact of the identified co-benefits on the cost curve is illustrated in three ways of distributing the impact of the three co-benefit categories.

Figure 15 below shows the median co-benefit of 96 (8 – 295) USD/tCO_2 for China. The orange curve represents the same cost curve for IMAGE from Figure 13. The darker blue line is the equally distributed median benefit and the lighter blue lines represent the 10th and 90th percentile of the identified co-benefit values respectively.

Applying the same equally distributed co-benefits to the estimated MACCs for both models illustrates the impact the shape of the curve has on the net-zero cost mitigation levels. As explained in section 3.2.1, the emission level is the amount of abated emissions, where the shifted MACC intersects with a carbon price of zero.

The lower carbon price and bigger amount of abatement in POLES compared to IMAGE result in larger emission levels at net-zero costs in POLES from the downward shift of the curve from the co-benefits, relative to the total abatement. While the emission level in IMAGE, from the median co-benefit, is 2.9 GtCO_2, the level for POLES in 2030 is 7.1 GtCO_2.

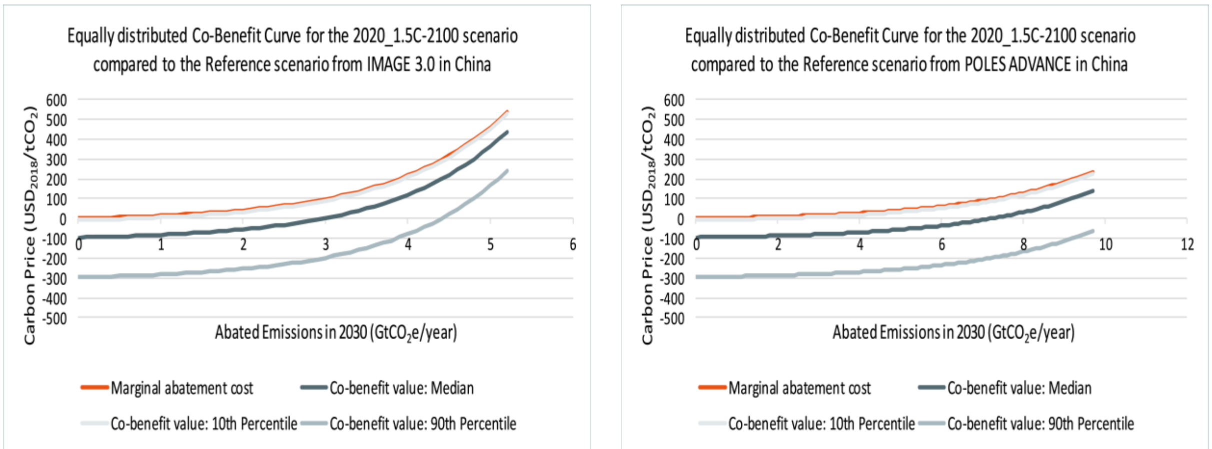

Figure 15: Impact of average, 10th and 90th percentile equally distributed co-benefit on the MACC in China for IMAGE 3.0 (left) and POLES ADVANCE (right)

For India, the median co-benefit was estimated to be 86 (54 – 369) USD/tCO_2. Applying the different co-benefit categories to the estimated MACC in India furthermore illustrates, that the median and 10th percentile estimates are much close together in India than it is the case for China, where there is a significant difference between both categories resulting in a bigger gap between the curves in China.

The development of both cost curves in India and therefore the shifted co-benefit curves as well is similar to the development in China. Again, the “flatter” shape of the cost curve in POLES coming from the lower carbon price compared to IMAGE results in the 90th percentile distribution not reaching a carbon price of zero before the total abatement of about 1.8 Gt in 2030. In general, the shape of the curve from POLES tends to result in larger emission levels than IMAGE which is mainly due to the combination of a larger mitigation gap and a lower carbon price in 2030 compared to IMAGE.

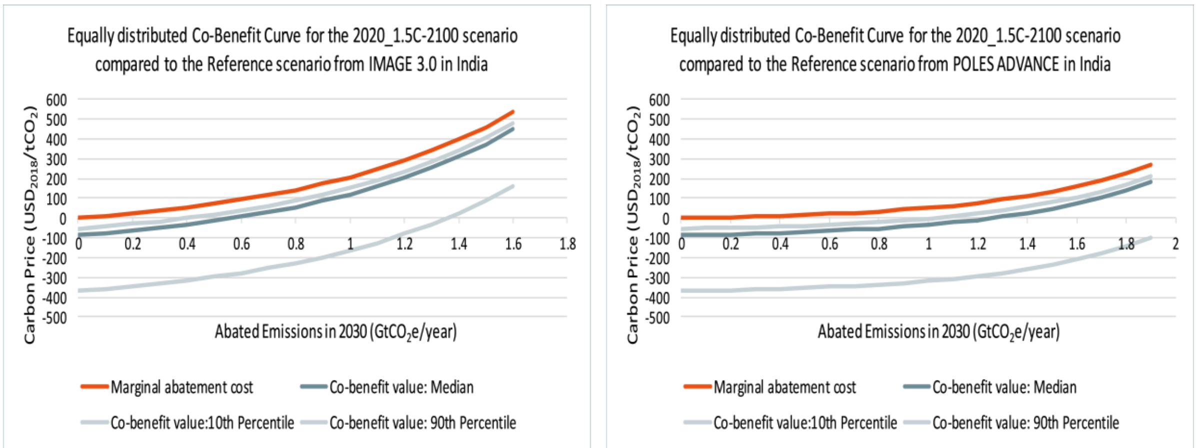

Figure 16: Impact of average, 10th and 90th percentile equally distributed co-benefit on the MACC in India for IMAGE 3.0 and POLES ADVANCE

In both countries, the equally distributed 90th percentile co-benefit leads to the curve having fully negative carbon prices. This is the result of one of the limitations explained in section 3.5. Due to the combination of the distribution type, as well as the carbon price and the applied co-benefit the downward shift of the curve results is large enough to keep the carbon price negative. The implication this has on the emission levels at net-zero costs, as well as the reduction potential of the total abatement cost, is shown in the following section.

The comparison of the three different distribution types, equal, Max_Min, and the 50% distribution, in China for both models is only illustrated using the median co-benefit. For the median co-benefit, the net-zero emission levels do not vary significantly (Figure 17). The flatter development of the curve in POLES, however, results in the different distribution curves being more spread out when crossing a carbon price of zero than it is the case for the curves from IMAGE. This is again the result of the lower carbon price for the total abated emissions in 2030 estimated by POLES. The net-zero cost emission levels in POLES are therefore varying more compared to the equal distribution than it is the case for IMAGE.

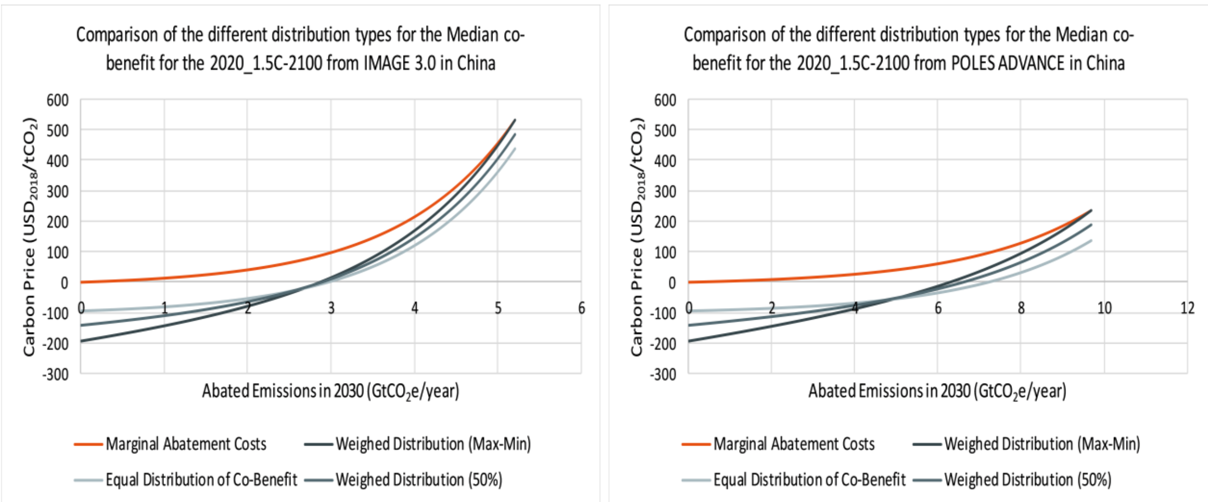

Figure 17: Comparison of the different distribution types for the median co-benefit for the 1.5°C scenario from IMAGE 3.0 and POLES ADVANCE in China

For India, the development of both curves and the impact of the different distribution types are similar. The flatter shape for the MACC from POLES results in net-zero cost emission levels from the distribution types, which are more spread out compared to IMAGE. Additionally, relative to the total abatement, the position of the intersection of the cost curves with a carbon price of zero is later in POLES than it is for IMAGE.

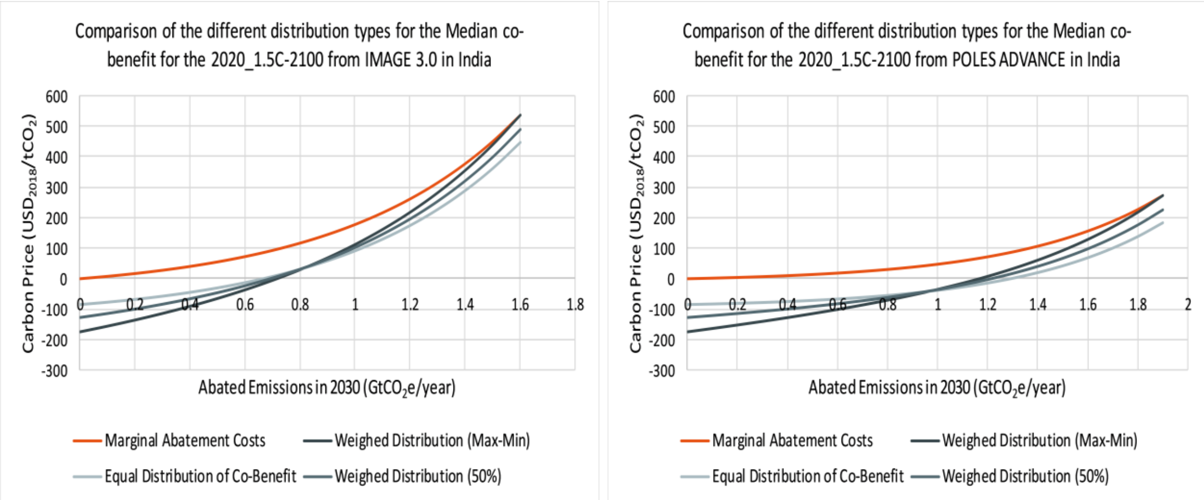

Figure 18: Comparison of the different distribution types for the median co-benefit for the 1.5°C scenario from IMAGE in China and India

It is, however, important to note, that the applied co-benefit has a significant impact on when applied via the different distribution types. The larger the applied co-benefit, the more spread out are the emission levels. In general, the Max-Min distribution results in the lowest emission levels out of the three distribution types, then the 50% distribution and the largest can be found when applying the co-benefits equally.

4.2.3 Impact on the Total Abatement Costs

Co-benefits occur after the successful implementation of mitigation options. As such, they do not reduce the initial investment required to implement the measures. When co-benefits are however considered as a share of the emission reduction from the implemented mitigation measures, then this share can also be seen as avoided investment in additional mitigation measures. Therefore it is possible to show the net-zero cost emission levels as a reduction in costs from the total abatement costs, provided by the IAM as the area under MACC.

The table below shows the total abatement costs compared to the total abatement costs including co-benefits for China. For this comparison, the equally distributed median co-benefit is displayed as well as the 10^{th} and 90^{th} percentile range.

Table 9: Total abatement cost with and without health co-benefits in China in 2030 for IMAGE and POLES

	Total Abatement Cost		
	with co-benefits	reduction (%)	no co-benefits
IMAGE 3.0	352 (620 - 80)	48 (8 - 88)	675
POLES	135 (512 - -39)	78 (15 - 106)	606

In IMAGE the health co-benefits in China cut the total abatement costs almost in half in 2030. For POLES this reduction is even more pronounced with a decrease of almost 80%. This can again be explained by the shape of the MACC the data from POLES results in. As mentioned in the previous sections, the MACC for POLES generally ends at a lower carbon price for the total abatement than it is the case for IMAGE. As a result of that, the curve has less of an inclination, resulting in higher emission levels at net-zero costs. The area under the curve between this emission level and the total abatement is, therefore, smaller compared to a curve with a higher carbon price and a steeper inclination.

For India, the general level of total abatement costs is lower than in China. When comparing however the percentage reduction, the decrease is similar in both countries. The reason for that is, that the chosen method always results in the same shape of the function. The only major variable influencing the shape of the curve is the carbon price in 2030. The individual carbon price per country is different, due to the way the IAMs calculate their scenarios however, the relation between the carbon prices is similar for both countries in both IAMs. As explained in section 2.2, the country-specific information is resulting from global optimization. The relation between different countries is therefore similar in this case since both regions for the IAMs follow the same underlying assumptions from the ADVANCE project (PIK, 2017).

Table 10: Total abatement cost with and without health co-benefits in India in 2030 for IMAGE and POLES

		Total Abatement Cost	
	with co-benefits	reduction (%)	no co-benefits
IMAGE 3.0	154 (186 - 14)	45 (34 - 94)	283
POLES	31 (51 - -19)	73 (56 - 116)	117

4.2.4 Emission Levels at Net-zero Costs

Depending on the type of distribution and the selected benefit, the net-zero emission levels differ in some cases significantly. Especially the choice of the co-benefit has the highest impact, while the emission level differs only slightly when changing the examined distribution method. All emission levels for China across all benefit ranges, distribution types and IAMs are displayed in Table 11 below.

Table 11: Results for the additional mitigation potential at net-zero costs in China in 2030 (in $GtCO_2$)

China					
			Equal	Max-Min	50%
IMAGE 3.0	1.5˚C	Median (10th - 90th Percentile)	3.0 (0.7 - 4.5)	2.9 (1 - 3.7)	2.9 (0.9 - 4.1)
POLES ADVANCE	1.5˚C	Median (10th - 90th Percentile)	7.2 (1.9 - 10.4)	6.3 (2.5 - 7.8)	6.7 (2.2 - 8.9)

Applying the median co-benefit value for China (96 USD_{2018}/t CO_2) results in a co-benefit emission level ranging from 2.9 $GtCO_2$ for the Max-Min distribution from IMAGE to 7.2 $GtCO_2$ for the 1.5°C scenario from POLES. The results further illustrate that the type of distribution has a much lower impact than expected with the difference between the distribution types averaging at less than 1 $GtCO_2$.

Displaying the results for the different variable combinations in comparison with the emission gap between the reference and the 1.5˚C mitigation scenario illustrates the relation between the net-zero cost emission reduction and its potential on covering the full emission gap. Figure 19 below illustrates this relationship.

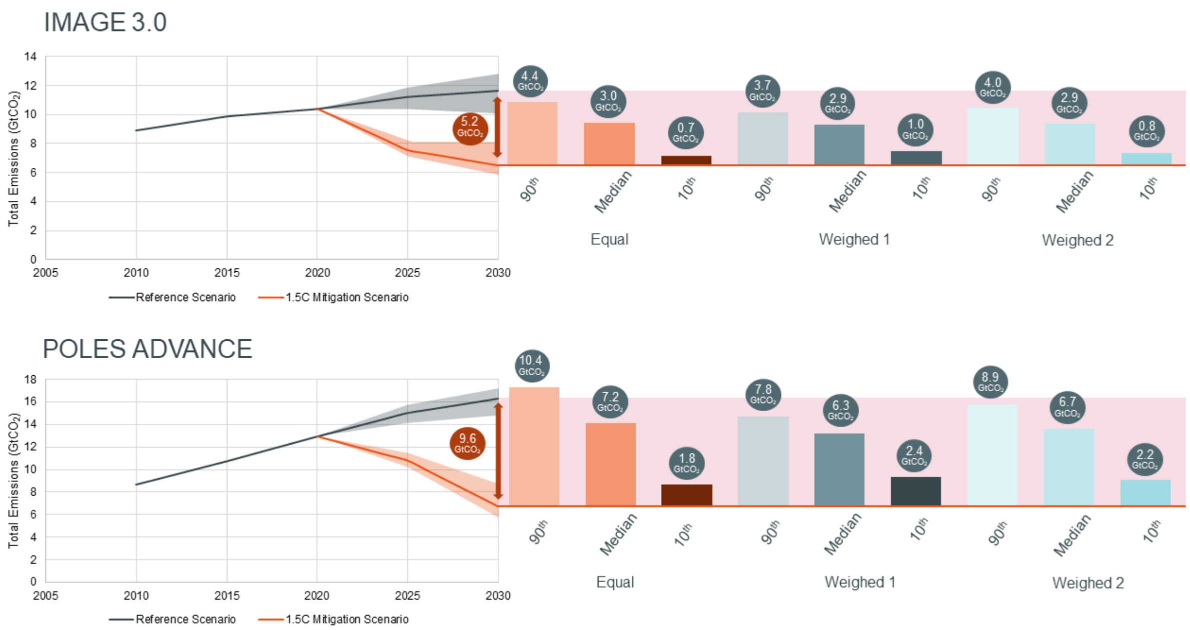

Figure 19: Net-Zero cost emission levels from three different co-benefit categories and distribution types compared to the emission gap between the 1.5˚C scenario and the reference for IMAGE and POLES in China in 2030

Figure 19 shows that the median co-benefit and the corresponding emission reduction is much closer to the 90^{th} percentile co-benefit estimates than the 10^{th} percentile. Both the median and 90^{th} percentile reductions cover in most cases more than 50% of the emission gap. Some estimates fall however out of the range of the other results as they project an overachievement of mitigation potential by the co-benefits as their abatement is higher than the emission gap. These cases can most likely be explained by the chosen method. With the applied approach, all cases where the co-benefit is higher than the carbon price for the maximum abatement in 2030 result in an overachievement of the gap.

With the identified emission levels at net-zero cost, the mitigation gap between the reference and the mitigation scenario can be closed. **Fehler! Verweisquelle konnte nicht gefunden werden.** below shows the emission levels of the median co-benefit compared to the total mitigation gap to illustrate how much the gap can be closed without imposing additional costs.

Table 12: Comparison of the emission levels at net-zero costs for China and it's potential for closing the mitigation gap in 2030

China					
			Equal	Max-Min	50%
IMAGE 3.0	1.5˚C	Median	3.0	2.9	2.9

		Share of Mitigation Gap	57%	55%	56%
POLES ADVANCE	1.5˚C	Median	7.2	6.3	6.7
		Share of Mitigation Gap	75%	66%	69%

The same applied co-benefits can close the emission gap estimated by POLES by a larger degree than the gap estimated by IMAGE even though the gap is much larger in POLES. This illustrates again the impact of the method, as it is again a result of the influence the carbon price has. Since the carbon prices are smaller for POLES than for IMAGE, the cost curve in POLES has much less of an inclination. This results in a greater impact of the ex-post applied co-benefit on the emission level, leading to a greater closing of the gap.

For India, the identified co-benefit potentials are on a lower level and closer together than those estimated for China. Compared to the results for China, especially the low spread between the different median results is interesting. While for China the results were differing in ranges of multiple Gt CO_2, the results for India move only between 1 Gt CO_2.

Table 13: Results of co-benefit mitigation potential in India (in $GtCO_2$)

India					
			Equal	Max-Min	50%
IMAGE 3.0	1.5˚C	Median (10th - 90th Percentile)	0.7 (0.5 - 1.4)	0.7 (1.8 - 5.2)	0.7 (0.6 - 1.3)
POLES ADVANCE	1.5˚C	Median (10th - 90th Percentile)	1.3 (1.1 - 2.1)	1.2 (1.1 - 1.6)	1.2 (1.1 - 1.8)

The Median estimates range from 0.7 to 1.3 $GtCO_2$. The biggest potential was identified for POLES.

When comparing net-zero cost emission levels to the mitigation gap between the reference for India and the 1.5˚C mitigation scenario, their impact in terms of emission reduction can be estimated. This comparison is illustrated in Figure 20 below.

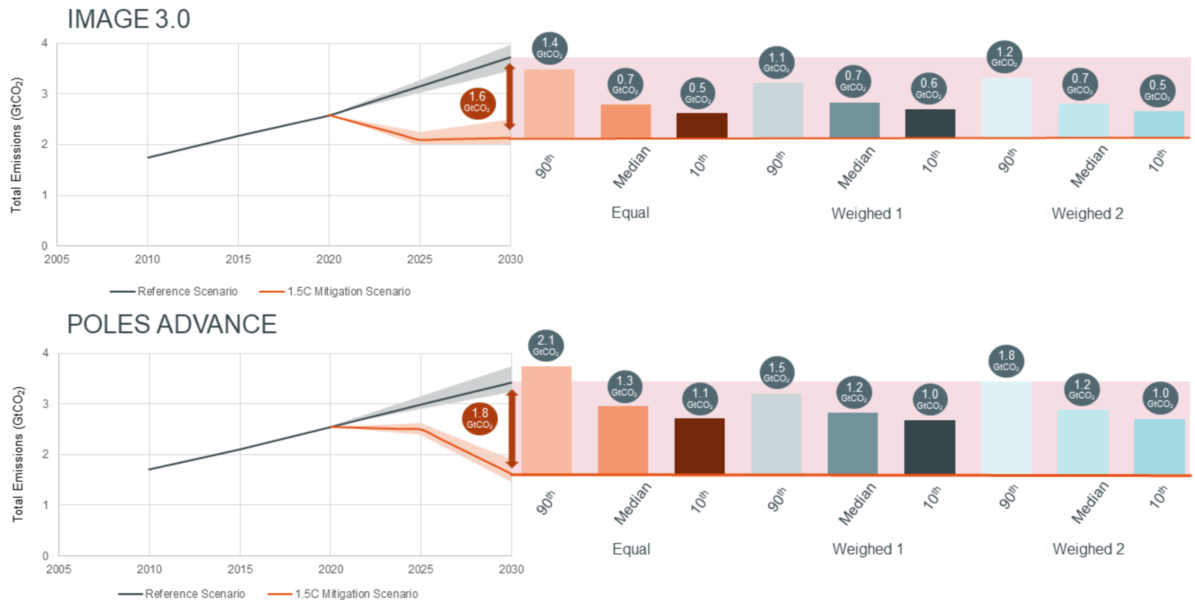

Figure 20: Net-Zero cost emission levels from three different co-benefit categories and distribution types compared to the emission gap between the 1.5˚C scenario and the reference for IMAGE and POLES in India in 2030

Compared to China, the Median and 90th percentile co-benefit estimates from POLES also cover more than 50% of the emission gap. Just for IMAGE, this observation is not valid. Here, only the 90th percentile co-benefit estimates cover more than 50% of the mitigation gap. The emission gap is, compared to the other three cases, for India about 0.5 $GtCO_2$ lower than the other estimates. The 90th percent co-benefit results in two distribution types in POLES in an equalization or overachievement of the mitigation gap.

For both countries, the overachievement of the mitigation gap was mostly found for the 90th percentile co-benefit in combination with the equal distribution. This is resulting from a combination of the characteristics of the distribution type and the carbon price. The equal distribution demands, that the co-benefit is equally subtracted from each step in emission reduction on the MACC until the total abatement in 2030 is reached. In the equal distribution, an overachievement can be reached as soon as the co-benefit is larger than the carbon price. Since POLES assumes a significantly lower carbon price than IMAGE and the 90th percentile co-benefit estimate is the largest of the three categories, it more often appears that the co-benefits have a bigger impact on POLES and can even lead to an overachievement of the mitigation gap.

The trends noticed for China continue also for India. In general, the mitigation gaps can be closed more in both scenarios estimated by POLES compared to IMAGE.

Table 14: Comparison of the emission levels at net-zero costs for China and it's potential for closing the mitigation gap in 2030

India					
			Equal	Max-Min	50%
IMAGE 3.0	1.5˚C	Median	0.7	0.7	0.7
		Share of Mitigation Gap	42%	45%	44%
POLES ADVANCE	1.5˚C	Median	1.3	1.2	1.2
		Share of Mitigation Gap	72%	64%	67%

The results show that already just health co-benefits could make up a significant share of the emission gap and reduce the total abatement costs. In some cases, with a high co-benefit estimate, the emission levels at net-zero cost were even greater than the mitigation gap. This suggests that the total abatement costs are also met and even overachieved which is confirmed by the cost reduction results illustrated in section 4.2.3.

The overachievement of the mitigation gap when applying the 90th percentile co-benefit via and equal distribution to the generated MACC for POLES is a result of the limitations of the method and the use of the provided input data. As explained in section 3.2, the combination of the equal distribution of a co-benefit higher than the carbon price in 2030 results in this overachievement. The only cases where the co-benefit was higher than the carbon price was for the 90th percentile co-benefit for the carbon prices from POLES.

The carbon prices for POLES are compared to IMAGE significantly lower in 2030. The reason for this can be found when viewing the carbon prices for the full assessment period from 2005 to 2100, which was used in the ADVANCE project (IIASA, 2019). As illustrated in section 3.2.1 for the case of India, the carbon price from IMAGE peak shortly after 2040 and then stagnate towards the end of the decade. For POLES, on the other hand, the carbon prices increase only marginal until 2030 and then increase drastically afterward until the end of the decade. This can explain why the carbon prices for POLES are lower than for IMAGE before 2030. The POLES IAM assumes a different mitigation strategy with much larger emission reductions and corresponding carbon prices in the second half of the decade whereas IMAGE assumes a steadier approach. As a result of that strategy, the carbon prices in 2030 in POLES are significantly lower than for IMAGE.

In general, the carbon prices used for this assessment are expected to be lower due to the type of IAM which was used. The assessment was limited to the type of IAMs, that delivered the for the method required input data, which were PE models. As stated in section 2.2, PE models estimate in comparison to GE models lower mitigation costs (Kriegler et al., 2015). Applying a similar method using GE models instead, could have resulted in lower emission levels at net-zero cost due to the higher cost and carbon price estimates expected with GE IAMs.

It is, however, important to note when the equal distribution was found to result in an overestimation of the emission levels, then the two unequal distribution types do not necessarily result in the same outcome as the results show. Since the curves for both unequal distributions are converging on the MACC, they would require a much higher co-benefit compared to the carbon price for the total emission reduction, as would be necessary for an overachievement with the equal distribution. Where the equal distribution just required a co-benefit value as high as the carbon price, the 50% distribution would require a co-benefit value 1.5 times higher than the carbon price. For the Max_Min distribution, an overachievement is not possible, since the carbon price of the co-benefit curve is equal to the estimated cost curve for the last abated emission in 2030. The two weighed distribution type could, therefore, be more robust for a greater variety of co-benefit and carbon price estimates than it is the case with the equal distribution.

5 Conclusion

This thesis identified the emission levels at net-zero costs from considering health co-benefits for a 1.5°C scenario from the IAMs IMAGE 3.0 and POLES ADVANCE in China and India for 2030. Multiple health co-benefit estimates have been extracted from literature and were aggregated. The marginal abatement costs were estimated using openly available data from the integrated assessment models IMAGE and POLES. Different types of distributing the co-benefits have been tested and their impact compared.

The identified emission levels at net-zero cost range for China from 2.9 to 7.2 (0.7 – 10.4) $GtCO_2$ in 2030. For India, the emission levels range from 0.7 to 1.3 (0.5 – 5.2) $GtCO_2$. Across all combinations, the identified emission levels in China made up a share of the mitigation gap for the 1.5°C scenario of about 63%. For India, the emission levels were on average smaller but still amounted to about 56% of the mitigation gap in 2030.

A lack of available data limited the scale of the assessment and increased uncertainties, since the limitations of the chosen input data carried through the assessment. Despite the limitations, the results are in line with other studies like Alexander et al. (2015). Although the results of the assessment are in line with previous research, the identified limitations of the method reduce its applicability for practical assessments regarding the use of the identified indicator.

While many previous studies focused on the potential of co-benefits in terms of a reduction of the mitigation cost, the applied method also provided the co-benefit potential in terms of emission savings in the form of a share of the emission gap. The health co-benefits in China and India in 2030 not only make up a significant share of the mitigation costs (Markandya et al., 2018; Vandyck et al., 2018), but can also be illustrated as more than 50% of the mitigation gap to the 1.5˚C pathway. In theory, this method could illustrate a dimension in the climate policy discourse which combines the already often discussed monetary aspects with their impact on reducing the emission gap and with that potentially increase ambition to act on climate change.

The negative impacts of climate change are dominating the current news already. Especially in developing nations like China and India, air pollution is a big problem. Co-benefits can especially in those countries illustrate the multiple benefits that climate mitigation can already have in the short term and reduce the financial burden these nations must take. They can illustrate for governments, that climate action does not only result in meeting the climate targets but also has an immediate effect on the country's population.

To come back to the, in the beginning, stated research objective. To answer whether co-benefits could be used to increase climate mitigation ambition depends on multiple perspectives. On the one hand, the results of this thesis should be a good incentive to increase ambitions due to the illustrated potential co-benefits provide. On the other hand, however, the many limitations coming from the characteristics of co-benefits and IAMs increase the uncertainty surrounding the results which could limit their usability to advise policymakers.

This thesis showed in simple terms the impact co-benefits could have on reducing climate mitigation costs and illustrated the results in terms of a share of the emission gap to the mitigation scenario, which would be created by considering co-benefits. The results can be an incentive for earlier action and prevent governments from postponing meaningful climate action.

5.1 Further Research and Implications for Climate Policy

The usability of the results could potentially be increased by choosing a different approach to bring co-benefits more into focus and reduce their uncertainties.

The role co-benefits could take in the context of climate policy discourse is still being discussed. Due to their heterogeneity and limitations, using them in the climate policy discourse as a measure to reduce climate mitigation costs could be difficult (Nemet et al., 2010). Not trying to monetize the co-benefits and only using physical measures to emphasize the benefit of climate mitigation could potentially have a bigger impact on the policy discourse (Nemet et al., 2010; Ürge-Vorsatz et al., 2014).

Co-benefits could be used to illustrate the benefits of climate mitigation in a local context where the assessment of potential co-benefits is easier to conduct. In a local context, it is possible to measure multiple co-benefits and create a systematic and integrated assessment. Here co-benefits could be used to illustrate the immediate positive effect of climate mitigation on the local circumstance which could increase societal acceptance and therefore reducing governmental burdens.

Furthermore, using co-benefits in a more local context would also help reduce the positive bias of the large-scale assessments since the assessment of the co-cost of the planned climate mitigation could be assessed more easily. This would further reduce the uncertainties of the approach applied in this thesis.

Using expert-based MACCs instead of IAM generated MACCs could further increase the usability in a local context since this would provide specific measure recommendation when combined with co-benefits. By knowing the individual measures and the co-benefit that could be attributed to them, governments would be able to identify the measures which would lead to the largest cost reduction from co-benefits and act on these options first, reducing the initial net-costs.

Especially the data from the IAM database seemed to cause issues with the method, coming from the limitations of these models. Amongst other things, this is the reason, why many authors are promoting to move away from full country economy-wide assessments to more sectoral and local assessment where multiple co-benefits can be estimated more comprehensively and where the impacts are illustrated not in monetary, but physical terms to increase the persuasiveness of the assessment (Ürge-Vorsatz et al., 2014; von Stechow et al., 2015). Illustrating the effect non-action could have in physical terms could also have a bigger impact on considering action than relying on IAM cost and emissions data from IAMs (Pindyck, 2017)

References

Alexander, R., Jeffery, L., Gütschow, J., Fyson, C., van Breevoort, P., Wouters, K., Deng, Y., Schaeffer, M., Hare, B., Sferra, F., Baarsch, F., Rocha, M., Höhne, N., Hagemann, M., Takeschi, K., Sterl, S., 2015. Climate Action Tracker: How climate change mitigation makes economic sense.

Anderson, K., Jewell, J., 2019. Debating the bedrock of climate-change mitigation scenarios [WWW Document]. Nature. URL https://www.nature.com/articles/d41586-019-02744-9#ref-CR19 (accessed 11.26.19).

Anenberg, S.C., Talgo, K., Arunachalam, S., Dolwick, P., Jang, C., West, J.J., 2011. Impacts of global, regional, and sectoral black carbon emission reductions on surface air quality and human mortality. Atmos. Chem. Phys. 11, 7253–7267. https://doi.org/10.5194/acp-11-7253-2011

Averchenkova, A., Bassi, S., Benes, K., Lagarde, A., Neuweg, I., 2016. Climate policy in China , the European Union and the United States : main drivers and prospects for the future – in depth country analyses Policy paper December 2016 Centre for Climate Change Economics and Policy Grantham Research Institute on Climate Cha 1–96.

Bertram, C., Bodirsky, B., Delsa, L., Humpenöder, F., Luderer, G., Popp, A., Creutzig, F., Fuss, S., Minx, J., von Stechow, C., 2019. Global greenhouse gas emission pathways until 2050. Umweltbundesamt (UBA), Dessau-Roßlau.

Blok, K., Nieuwlaar, E., 2016. Introduction to Energy Analysis, 2nd ed. Routledge, London. https://doi.org/https://doi.org/10.4324/9781315617213

Bockel, L., Macleod, M., Henderson, B., 2012. Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climate Smart Agriculture Policy Options. FAO.

Bodansky, D., 2015. Reflections on the Paris Conference - Opinio Juris [WWW Document]. URL http://opiniojuris.org/2015/12/15/reflections-on-the-paris-conference/ (accessed 10.22.19).

Bollen, J., Guay, B., Jamet, S., Corfee-Morlot, J., 2009. Co-benefits of Climate Change Mitigation Policies. OECD iLibrary ECO/WKP. https://doi.org/10.1787/224388684356

Bruce, J.P., Yi, H., Haites, E.F., Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J.A., Grubb, M.J., Parson, E.A., Richels, R.G., Rotmans, J., Shukla, P.R., Tol, R.S.J., Cline, W.R., 1996. Integrated assessment of climate change: an overview and comparison of approaches and results. Contribution of the Intergovernmental Panel on Climate Change Working Group III. 367–396.

Bundesregierung Deutschland, 2016. Bund fördert Photovoltaik-Batteriespeicher [WWW Document]. URL https://www.bundesregierung.de/Content/DE/Artikel/2016/03/2016-03-01-batteriespeicher-foerderung.html (accessed 3.19.18).

Carbon Brief, 2018. How integrated assessment models are used to study climate change [WWW Document]. URL https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change (accessed 10.24.19).

Cherp, A., Jewell, J., Vinichenko, V., Bauer, N., De Cian, E., 2013. Global Energy Security under Different Climate Policies, GDP Growth Rates and Fossil Resource Availabilities. J. Chem. Inf. Model. 53, 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Climate Action Tracker, 2019. China | Climate Action Tracker [WWW Document]. URL https://climateactiontracker.org/countries/china/ (accessed 9.23.19).

Climate Analytics, NewClimate Institute, Ecofys, 2018. Climate Action Tracker [WWW Document]. URL https://climateactiontracker.org/ (accessed 4.10.19).

Day, T., Gonzales-Zuñiga, S., Nascimento, L., Höhne, N., Fekete, H., Sterl, S., Hans, F., Warembourg, A., Anica, A., Van Breevoort, P., 2018. Climate Opportunity: More Jobs; Better Health; Liveable Cities.

den Elzen, M., Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H., Fransen, T., Keramidas, K., Roelfsema, M., Sha, F., van Soest, H., Vandyck, T., 2019. Are the G20 economies making enough progress to meet their NDC targets? Energy Policy 126, 238–250. https://doi.org/10.1016/j.enpol.2018.11.027

den Elzen, M., Lucas, P., 2003. FAIR 2.0 - A decision-support tool to assess the environmental and economic consequences of future climate regimes 91.

Deng, H.M., Liang, Q.M., Liu, L.J., Anadon, L.D., 2017. Co-benefits of greenhouse gas mitigation: A review and classification by type, mitigation sector, and geography. Environ. Res. Lett. 12. https://doi.org/10.1088/1748-9326/aa98d2

Fekete, H., Höhne, N., Hagemann, M., Wehnert, T., Mersmann, F., Vierweg, M., Rocha, M., Schaeffer, M., Hare, W., 2013. Emerging economies - potentials, pledges and fair shares of greenhouse gas reductions, Chemical Modeling for Air Resources. Umweltbundesamt (UBA), Dessau-Roßlau. https://doi.org/10.1016/B978-0-12-408135-2.00007-0

Garg, A., 2011. Pro-equity Effects of Ancillary Benefits of Climate Change Policies: A Case Study of Human Health Impacts of Outdoor Air Pollution in New Delhi. World Dev. 39, 1002–1025. https://doi.org/10.1016/j.worlddev.2010.01.003

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. 114, 11645–11650. https://doi.org/10.1073/pnas.1710465114

Hammitt, J.K., 2000. Valuing mortality risk: Theory and practice. Environ. Sci. Technol. 34, 1396–1400. https://doi.org/10.1021/es990733n

Hare, B., Brecha, R., Schaeffer, M., 2018. Integrated Assessment Models : what are they and how do they arrive at their conclusions? Clim. Anal. 1–12.

He, K., Lei, Y., Pan, X., Zhang, Y., Zhang, Q., Chen, D., 2010. Co-benefits from energy policies in China. Energy 35, 4265–4272. https://doi.org/10.1016/j.energy.2008.07.021

HM Treasury, 2003. The Green Book: Appraisal and Evaluation in Central Government, Treasury Guidance. London Her Majesty's Station. Off. 118.

IIASA, 2019. ADVANCE Synthesis Scenario Database (version 1.0) [WWW Document]. URL https://db1.ene.iiasa.ac.at/ADVANCEDB/dsd?Action=htmlpage&page=10#citation (accessed 9.23.19).

IPCC, 2018a. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. Intergovernmental Panel on Climate Change.

IPCC, 2018b. Summary for Policymakers., Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. World Meteorological Organization, Geneva, Switzerland. https://doi.org/10.1017/CBO9781107415324

IPCC, 2014a. Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. https://doi.org/10.1017/CBO9781107415416

IPCC, 2014b. Climate Change 2014: Mitigation of Climate Change. Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Cambridge University Press, United Kingdom and New York, NY, USA. https://doi.org/10.1017/CBO9781107415416

IRENA, 2016. The True Cost of Reducing Fossil Fuels: Saving on the Externalities of Air Pollution and Climate Change. IRENA.

Jenner, S., Lamadrid, A.J., 2013. Shale gas vs. coal: Policy implications from environmental impact comparisons of shale gas, conventional gas, and coal on air, water, and land in the United States. Energy Policy 53, 442–453. https://doi.org/10.1016/j.enpol.2012.11.010

Jewell, J., Cherp, A., Vinichenko, V., Bauer, N., Kober, T., McCollum, D., van Vuuren, D.P., van der Zwaan, B., 2013. Energy Security of China, India, the EU and the US under Long-Term Scenarios: Results from Six IAMs. Clim. Chang. Econ. 04, 1340011. https://doi.org/10.1142/s2010007813400113

Jewell, J., Vinichenko, V., Mccollum, D., Bauer, N., Riahi, K., Aboumahboub, T., Fricko, O., Harmsen, M., Kober, T., Krey, V., 2016. Comparison and interactions between the long-term pursuit of energy independence and climate policies. Nat. Energy 1. https://doi.org/10.1038/NENERGY.2016.73

Jung, K.H., Yan, B., Moors, K., Chillrud, S.N., Perzanowski, M.S., Whyatt, R.M., Hoepner, L., Goldstein, I., Zhang, B., Camann, D., Kinney, P.L., Perera, F.P., Miller, R.L., 2012. Repeated exposure to polycyclic aromatic hydrocarbons and asthma: effect of seroatopy. Ann Allergy Asthma Immunol 109, 249–254. https://doi.org/10.1016/j.anai.2012.07.019

Kelly, D. L., & Kolstad, C.D., 2000. Integrated assessment models for climate change control. Int. Yearb. Environ. Resour. Econ. 171–197.

Kesicki, F., 2011. Marginal Abatement Cost Curves for Policy Making – Expert-Based vs . Model-Derived Curves. IAEE Int. Conf. 1–19. https://doi.org/http://www.homepages.ucl.ac.uk/~ucft347/Kesicki_MACC.pdf

Kesicki, F., Ekins, P., 2012. Marginal abatement cost curves : a call for caution. Clim. Policy 12, 219–236. https://doi.org/10.1080/14693062.2011.582347

Kinley, R., 2017. Climate change after Paris: from turning point to transformation. Clim. Policy 17, 9–15. https://doi.org/10.1080/14693062.2016.1191009

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V.J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C., Van Vuuren, D.P., 2015. Diagnostic indicators for integrated assessment models of climate policy. Technol. Forecast. Soc. Change 90, 45–61. https://doi.org/10.1016/j.techfore.2013.09.020

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., van Vuuren, D.P., 2014. The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. Clim. Change 123, 353–367. https://doi.org/10.1007/s10584-013-0953-7

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37, 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Markandya, A., Armstrong, B.G., Hales, S., Chiabai, A., Criqui, P., Mima, S., Tonne, C., Wilkinson, P., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. Lancet 374, 2006–2015. https://doi.org/10.1016/S0140-6736(09)61715-3

Markandya, A., Smith, S.J., Arto, I., Van Dingenen, R., Sampedro, J., González-Eguino, M., Pizarro-Irizar, C., 2018. Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. Lancet Planet. Heal. 2, e126–e133. https://doi.org/10.1016/s2542-5196(18)30029-9

Mayrhofer, J.P., Gupta, J., 2016. Environmental Science & Policy The science and politics of co-benefits in climate policy. Environmntal Sci. Policy 57, 22–30.

McCollum, D., Riahi, K., Krey, V., Makowski, M., Nakicenovic, N., Kolp, P., Grubler, A., 2013. Climate policies can help resolve energy security and air pollution challenges. Clim. Change 119, 479–494. https://doi.org/10.1007/s10584-013-0710-y

Mendelsohn, R., Dinar, A., Williams, L., 2006. The distributional impact of climate change on rich and poor countries. Environ. Dev. Econ. 11, 159–178. https://doi.org/10.1017/S1355770X05002755

Miyatsuka, A., Zusman, E., 2015. What are Co-benefits ? ACP Fact Sheet No . 1 1–2.

Nemet, G.F., Holloway, T., Meier, P., 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. Environ. Res. Lett. 5. https://doi.org/10.1088/1748-9326/5/1/014007

Nicoletti, Giovanni, Arcuri, N., Nicoletti, Gerardo, Bruno, R., 2015. A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers. Manag. 89, 205–213. https://doi.org/10.1016/j.enconman.2014.09.057

OECD, 2012. Mortality Risk Valuation in Environment, Health and Transport Policies. OECD Publishing. https://doi.org/https://doi.org/10.1787/9789264130807-en

Östblom, G., Samakovlis, E., 2007. Linking health and productivity impacts to climate policy costs: A general equilibrium analysis. Clim. Policy 7, 379–391. https://doi.org/10.1080/14693062.2007.9685663

Paltsev, S., Capros, P., 2013. Cost Concepts for Climate Change Mitigation. Clim. Chang. Econ. 04, 1340003. https://doi.org/10.1142/s2010007813400034

Parry, I., Veung, C., Heine, D., 2015. How Much Carbon Pricing is in Countries own Interests? The Critical Role of Co-Benefits., Discussion Paper 2015. Harvard Project on Climate Agreements, Cambridge. https://doi.org/10.5089/9781498358279.001

PBL, 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0. PBL Netherlands Environmental Assessment Agency, The Hague.

Pearce, D., 2000. Policy Frameworks for the Ancillary Benefits of Climate Change Policies (No. GEC 2000-1).

Perera, F.P., 2017. Multiple threats to child health from fossil fuel combustion: Impacts of air pollution and climate change. Environ. Health Perspect. 125, 141–148. https://doi.org/10.1289/EHP299

PIK, 2017. The ADVANCE project [WWW Document]. URL http://www.fp7-advance.eu/ (accessed 9.23.19).

Pindyck, R.S., 2017. The use and misuse of models for climate policy. Rev. Environ. Econ. Policy 11, 100–114. https://doi.org/10.1093/reep/rew012

Pindyck, R.S., 2013. CLIMATE CHANGE POLICY: WHAT DO THE MODELS TELL US? J. Econ. Lit.

Ripple, W.J., Wolf, C., Newsome, T.M., 2019. World Scientists ' Warning of a Climate Emergency. Biosci. Mag. 2000, 1–20.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °c. Nature 534, 631–639. https://doi.org/10.1038/nature18307

Rogelj, J., McCollum, D.L., Reisinger, A., Meinshausen, M., Riahi, K., 2013. Probabilistic cost estimates for climate change mitigation. Nature 493, 79–83. https://doi.org/10.1038/nature11787

Rosen, R.A., Guenther, E., 2015. The economics of mitigating climate change: What can we know? Technol. Forecast. Soc. Change 91, 93–106. https://doi.org/10.1016/j.techfore.2014.01.013

Roston, E., Tartar, A., 2019. China's and India's Fight Against Pollution While Modernizing - Bloomberg [WWW Document]. Bloom. Businessweek. URL https://www.bloomberg.com/news/features/2018-11-02/china-s-and-india-s-fight-against-pollution-while-modernizing (accessed 9.23.19).

Ruth, M., 2011. Managing Regional Climate Mitigation and Adaptation Co-benefits and Co-costs, in:

Zimmermann, K.-O. (Ed.), Resilient Cities. Cities and Adaptation to Climate Chnage. Springer, pp. 205–2012. https://doi.org/10.1007/978-94-007-0785-6_14

Sobhani, N., 2018. The Role of Co-Benefits: Rethinking The Costs and Benefits of Climate Change Mitigation - Niskanen Center [WWW Document]. URL https://www.niskanencenter.org/the-role-of-co-benefits-rethinking-the-costs-and-benefits-of-climate-change-mitigation/ (accessed 11.29.19).

Sovacool, B.K., 2017. Cobenefits and Trade-Offs of Green and Clean Energy: Evidence from the Academic Literature and Asian Case Studies. Ssrn. https://doi.org/10.2139/ssrn.2894768

Sovacool, B.K., Brown, M.A., 2010. Competing Dimensions of Energy Security: An International Perspective. Ssrn. https://doi.org/10.1146/annurev-environ-042509-143035

Stern, N., 2016. Economics: Current climate models are grossly misleading. Nature 530, 407–409. https://doi.org/10.1038/530407a

The Economist, 2019. Costing the earth - Countries most exposed to climate change face higher costs of capital | Finance and economics | The Economist [WWW Document]. URL https://amp-economist-com.proxy.library.uu.nl/finance-and-economics/2019/08/15/countries-most-exposed-to-climate-change-face-higher-costs-of-capital?__twitter_impression=true (accessed 11.13.19).

The New Climate Economy, 2015. New Climate Economy technical note: Quantifying the multiple benefits from low-carbon actions in a greenhouse gas abatement cost curve framework. The New Climate Economy.

The Washington Post, 2019. Delhi pollution: Air quality reaches toxic levels as India loses battle against polluters - The Washington Post [WWW Document]. URL https://www.washingtonpost.com/world/indias-losing-battle-against-pollution-delhi-air-quality-reaches-toxic-levels-again/2019/11/04/0901f378-fecc-11e9-8341-cc3dce52e7de_story.html (accessed 11.8.19).

Tzivian, L., 2011. Outdoor air pollution and asthma in children. J. Asthma 48, 470–481. https://doi.org/10.3109/02770903.2011.570407

UNEP, 2018. The Emissions Gap Report 2018. United Nations Environment Programme (UNEP), Nairobi.

UNFCCC, 2018. Summary of the Paris Agreement [WWW Document]. URL https://unfccc.int/resource/bigpicture/#content-the-paris-agreemen (accessed 4.10.19).

UNFCCC, 2015. Paris Agreement – Decision 1/CP.21 – Report of the Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum Part two: Action taken by the Conference ofthe Parties at its twenty-first, Addendum-Part two: action taken by the Conference of the Parties. Bonn.

UNFCCC, 2006. Training Handbook on Mitigation Assessment for Non-Annex I Parties. UNFCCC.

United Nations, 2019. The sustainable development goals report 2019. United Nations Publ. issued by Dep. Econ. Soc. Aff.

United Nations Environmental Programm (UNEP), 2000. Natural Selection: Evolving Choices for Renewable Energy Technology and Policy. United Nations, New York.

Ürge-Vorsatz, D., Herrero, S.T., Dubash, N.K., Lecocq, F., 2014. Measuring the Co-Benefits of Climate Change Mitigation. Annu. Rev. Environ. Resour. 39, 549–582. https://doi.org/10.1146/annurev-environ-031312-125456

Ürge-Vorsatz, D., Kelemen, A., Tirado-Herrero, S., Thomas, S., Thema, J., Mzavanadze, N., Hauptstock, D., Suerkemper, F., Teubler, J., Gupta, M., Chatterjee, S., 2016. Measuring multiple impacts of low-carbon energy options in a green economy context. Appl. Energy 179, 1409–1426. https://doi.org/10.1016/j.apenergy.2016.07.027

Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J. V., Van Dingenen, R., Holland, M., Saveyn, B., 2018. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris

Agreement pledges. Nat. Commun. 9, 1–11. https://doi.org/10.1038/s41467-018-06885-9

von Stechow, C., Jan, C.M., Keywan, R., Jessica, J., David, L.M., Max, W.C., Christoph, B., Gunnar, L., Giovanni, B., 2016. 2 °C and SDGs: united they stand, divided they fall? Environ. Res. Lett. 11, 34022. https://doi.org/10.1088/1748-9326/11/3/034022

von Stechow, C., McCollum, D., Riahi, K., Minx, J., Kriegler, E., van Vuuren, D.P., Jewell, J., Robledo-Abad, C., Hertwich, E., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N.K., Bollen, J.C., Ürge-Vorsatz, D., Edenhofer, O., 2015. Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annu. Rev. Environ. Resour. https://doi.org/10.1146/annurev-environ-021113-095626

Wagner, F., Amann, M., Borken-Kleefeld, J., Cofala, J., Höglund-Isaksson, L., Purohit, P., Rafaj, P., Schöpp, W., Winiwarter, W., 2012. Sectoral marginal abatement cost curves: Implications for mitigation pledges and air pollution co-benefits for Annex I countries. Sustain. Sci. 7, 169–184. https://doi.org/10.1007/s11625-012-0167-3

Watson, R., McCarthy, J.J., Canziani, P., Nakicenovic, N., Hisas, L., 2019. The Truth Behind the Climate Pledges. FEU-US. https://doi.org/10.1017/CBO9781107415324.004

Wei, M., Patadia, S., Kammen, D.M., 2010. How Many Jobs Can The Clean Energy Industry Generate in the U.S.? Energy Policy 38, 919–931. https://doi.org/doi:10.1016/j.enpol.2009.10.044

West, J.J., Janssens-Maenhout, G., Williams, M., Schwartz, J., Ramanathan, V., Muller, N.Z., Pozzoli, L., Faluvegi, G., Anenberg, S.C., Van Dingenen, R., Klimont, Z., Raes, F., Hicks, W.K., Vignati, E., Shindell, D., Emberson, L., Demkine, V., Kuylenstierna, J., Amann, M., 2012. Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. Environ. Health Perspect. 120, 831–839. https://doi.org/10.1289/ehp.1104301

West, J.J., Smith, S.J., Silva, R. a, Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., Horowitz, L.W., Lamarque, F., 2013. Co-benefits of Global Greenhouse Gas Mitigation for Future Air Quality and Human Health. Nat. Clim. Chang. 3, 885–889. https://doi.org/10.1038/NCLIMATE2009.Co-benefits

WHO, 2009. Global Health Risks. Mortality and burden of disease attributable to selected major risks.

Wilkinson, P., Smith, K.R., Davies, M., Adair, H., Armstrong, B.G., Barrett, M., Bruce, N., Haines, A., Hamilton, I., Oreszczyn, T., Ridley, I., Tonne, C., Chalabi, Z., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. Lancet 374, 1917–1929. https://doi.org/10.1016/S0140-6736(09)61713-X

Woodcock, J., Edwards, P., Tonne, C., Armstrong, B.G., Ashiru, O., Banister, D., Beevers, S., Chalabi, Z., Chowdhury, Z., Cohen, A., Franco, O.H., Haines, A., Hickman, R., Lindsay, G., Mittal, I., Mohan, D., Tiwari, G., Woodward, A., Roberts, I., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet 374, 1930–1943. https://doi.org/10.1016/S0140-6736(09)61714-1

World Bank, 2019. GDP deflator (base year varies by country) - United States | Data [WWW Document]. URL https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS?end=2018&locations=US&start=2005&view=chart&year=2018 (accessed 10.24.19).

Yi, H., 2013. Clean energy policies and green jobs: An evaluation of green jobs in U.S. metropolitan areas. Energy Policy 56, 644–652. https://doi.org/10.1016/j.enpol.2013.01.034

Acknowledgments

First and foremost I would like to thank NewClimate Institute for allowing me to write this thesis in collaboration with them at their office in Cologne, Germany. I would like to thank all my colleagues at the office for welcoming me nicely and for maintaining a great working environment throughout the thesis period. I also want to thank my two supervisors from NewClimates's side, Takeshi Kuramochi and from Utrecht University, Robert Harmsen for the supervision and advice throughout the research.

Appendix

Appendix 1 – Previous attempts of estimating a MACC in 2030

It was first attempted to take the carbon prices as Y-coordinate and the abated emissions as X-coordinate from different mitigation scenarios. With these different points, it was attempted to draw one consistent cost curve. It, however, was not possible to link the points together in a sensible manner. The reasoning behind that is, that the IAMs assume different measure packages for each scenario, making the individual endpoints for each scenario impossible to compare to each other rendering the attempt unfeasible.

One, therefore, had to stay inside one scenario to draw a cost curve. The origin of all cost curves is always the point (0/0), since cost curves, as explained earlier, always assume zero costs for zero abatements. Together with the earlier defined "endpoint" consisting out of the mitigation gap and the carbon price at the gap as x and y, one had two points illustrating a straight function. The model derived cost curves are not represented by a straight line but rather assume exponentially increasing costs with increasing abatement resulting in a slanted curve being convex to the x-axis. It, therefore, required another reference point to justify this slanted curve. For this, the Area under MACC reported in the IAM was chosen. As mentioned earlier, it was assumed that the origin of this value was linked to the other two indicators withdrawn from the IAM database. If that would have been the case, all estimated curves would have followed the desired shape and would be constant with each other.

To implement the Area under the MACC into the estimation of the shape of the curve, Different types of functions could be feasible. Potential options were a polynomial function with the limit to a two-degree function due to the number of input parameters available, an exponential function and a logarithmic function. Since on point of the curve is 0, the logarithmic function is not possible to use, leaving the other two function types. First, it was attempted to create a polynomial function using the three input parameters as Anker points. The general expression of the function is shown in Equation 1:

$$f(x) = y = ax^2 + bx \qquad \text{Equation 1}$$

Where the parameters a and b are the determining variables influencing the shape of the curve. However, the shape of the estimated MACC in 2030 should not be arbitrary but rather be based on another Anker point reported in the database. For this, the Area under the MACC from the database was chosen. The determined function, therefore, has to go through the origin and the endpoint but also have an area under the equal to the pre-requisite. Therefore, the integer of Function 1 had be created which is shown in Function 2.

$$F(x) = A = \frac{a}{3}x^3 + \frac{b}{2}x^2 \qquad \text{Equation 2}$$

Both functions were then used and re-formed to find the generic forms of the parameters a and b. The equation used for parameters a and b is represented in Functions 3 and 4.

$$a = \frac{3(xy-2A)}{x^3} \qquad \text{Equation 3} \qquad\qquad b = \frac{6A-2xy}{x^2} \qquad \text{Equation 4}$$

When filling in the abated emissions (x), the carbon price (y) and the Area und MACC (A) for each scenario the corresponding parameters can be calculated. When these parameters are filled in Function 1 the cost curve for different abatement levels up to the maximum abatement can be calculated.

However, for some combinations of input parameters, this type of function resulted in weirdly shaped curves. For instance, in some cases, the curve dipped into the negative value range of y-values at the beginning. In others, the curve was “bloating” up, meaning it was convex to the x-axis. Both versions do not make sense in the context of a cost curve resulting from an IAM.

Appendix 2

Table 2: Long list of benefits. Abbreviations for evidence: l = limited, m = medium, r = robust; for agreement: l = low, m = medium, h = high (IPCC, 2014a)

Economic, social and environmental co-impacts per sector and mitigation measures

Sector	Mitigation measure	Co-impact (level of evidence/ agreement on effect): Economic	Social	Environmental
Energy Supply	**Nuclear replacing coal**	Energy security (reduced exposure to price volatility) (m/m), local employment effect (but uncertain net effect) (l/m), legacy/cost of waste and abandoned reactors (m/h)	Mixed health impact via reduced air pollution and coal mining accidents (m/h), nuclear accidents and waste treatment, uranium mining and drilling (m/l); safety and waste concerns (r/h); proliferation risk (m/m)	Mixed ecosystem impact via reduced air pollution (m/h) and coal mining (l/h), nuclear accidents (m/m)
	Renewable energy (wind, PV, CSP, Hydro, geothermal, bioenergy) replacing coal	Energy security (r/m); local employment (but uncertain net effect) (m/m); water management (for some hydro energy) (m/h); extra measures to match demand (for PV, wind some CSP) (r/h); higher use of critical metals for PV and direct drive wind turbines (r/m)	Reduced health impact via reduced air pollution (except bioenergy) (r/h) and coal mining accidents (m/h); contribution to (off-grid) energy access (m/l); threat of displacement (for large hydro installations) (m/h)	Mixed ecosystem impact via reduced air pollution (except bioenergy) (m/h) and coal mining (l/h), habitat impact (for some hydro energy) (m/m), landscape and wildlife impact (m/m); lower/ higher water use (for Wind, PV (m/m); bioenergy, CSP, geothermal and reservoir hydro (m/h))
	Fossil energy with CCS replacing coal	Preservation vs. lock-in of human and physical capital in the fossil industry (m/m); long-term monitoring of CO_2 storage (m/h)	Health impact via risk of CO_2 leakage (m/m) and additional upstream supply-chain activities (m/h); safety concern (CO_2 storage and transport) (m/h)	Ecosystem impact via additional upstream supply-chain activities (m/m) and higher water use (m/h)
	CH4 leakage prevention, capture or treatment	Energy security (potential to use gas in some cases) (l/h)	Reduced health impact via reduced air pollution (m/m); occupational safety at coal mines (m/m)	Reduced ecosystem impact via reduced air pollution (l/m)
Transport	**Reduction of carbon intensity of fuel**	Energy security (diversification, reduced oil dependence and exposure to oil price volatility) (m/m); technological spill overs (l/l)	Mixed health impact via increased/reduced urban air pollution by electricity and hydrogen (r/h), diesel (l/m); road safety concerns (l/l) but reduced health impact via reduced noise (l/m) of electric LDVs	Mixed ecosystem impact of electricity and hydrogen via reduced urban air pollution (m/m) and material use (unsustainable mining) (l/l)
	Reduction of energy intensity	Energy security (reduced oil dependence and exposure to oil price volatility) (m/m)	Reduced health impact via reduced urban air pollution (r/h); road safety (crash-worthiness depending on the design of the standards) (r/h)	Reduced ecosystem and biodiversity impact via reduced air pollution (r/h) and land use competition (m/m)

	Compact urban form and improved transport infrastructure Modal shift	Energy security (reduced oil dependence and exposure to oil price volatility) (m/m); productivity (reduced urban congestion/ travel times, walking) (r/h)	Mixed health impact for non-motorized modes via increased physical activity (r/h), potentially higher exposure to air pollution (r/h), reduced noise (via modal shift and travel reduction) (r/h); equitable mobility access to employment opportunities (r/h); road safety (via modal shift) (r/h)	Reduced ecosystem impact via reduced urban air pollution (r/h) and land use competition (m/m)
	Journey distance reduction and avoidance	Energy security (reduced oil dependence and exposure to oil price volatility) (r/h); productivity (reduced urban congestion/ travel times, walking) (r/h)	Reduced health impact (for non-motorized transport modes) (r/h)	Mixed ecosystem impact via reduced urban air pollution (r/h), new/ shorter shipping routes (r/h); reduced land use competition from transport infrastructure (r/h)
Buildings	**Reduction of GHG emissions intensity (e.g., fuel switching, RES incorporation, green roofs)**	Energy security (m/h); employment impact (m/m); lower need for energy subsidies (l/l); asset values of buildings (l/m)	Fuel poverty alleviation via reduced energy demand (m/h); energy access (for higher energy cost) (l/m); productivity time for women/ children (for replaced traditional cookstoves) (m/h)	Reduced health impact in residential buildings and ecosystem impact (via reduced fuel poverty (r/h), indoor/ outdoor air pollution (r/h) and UHI effect) (l/m); urban biodiversity (for green roofs) (m/m)
	Retrofits of existing buildings Exemplary new buildings Efficient equipment	Energy security (m/h); employment impact (m/m); lower need for energy subsidies (l/l); asset value of buildings (l/m); disaster resilience (l/m)	Fuel poverty alleviation via reduced energy demand (for retrofits and efficient equipment) (m/h); energy access (higher housing cost) (l/m); thermal comfort (m/h); productivity time for women/ children (for replaced traditional cookstoves) (m/h)	Reduced health and ecosystem impact (e.g. via reduced fuel poverty (r/h), indoor/outdoor air pollution (r/h), UHI effect (l/m), improved indoor environmental conditions (m/h)); health risk via insufficient ventilation (m/m); reduced water

				consumption and sewage production (l/l)
	Behavioural changes reducing energy demand	Energy security (m/h); less need for energy subsidies (l/l)		Reduced health and ecosystem impact (e.g. via reduced improved indoor environmental conditions (m/h) and less outdoor air pollution (r/h))
Industry	**Reduction of CO_3/ non-CO_2 GHG emission intensity**	Competitiveness and productivity (m/h)	Reduced health impact via reduced air pollution and better working conditions (PFC from aluminium) (m/m)	Reduced ecosystem impact (via reduced local air pollution and water pollution) (m/m); water conservation (l/m)
	Technical energy efficiency improvements via new processes/technologies	Energy security (via lower energy intensity) (m/m); employment impact (l/l); competitiveness and productivity (m/h); technological spill overs in DCs (l/l)	Reduced health impact via reduced local air pollution (l/m); new business opportunities (m/m); increased water availability and quality (l/l); improved safety, working conditions and job satisfaction (m/m)	Reduced ecosystem impact via reduced local air and water pollution and waste material disposal (m/m); reduced use of raw/virgin materials and natural resources implying reduced unsustainable resource mining (l/l)
	Product demand reductions	Decreased national sales tax revenue in the medium term (l/l)	Increased wellbeing via diver's lifestyle choices (l/l)	Reduced post-consumption waste (l/l)

AFOLU	Supply side: forestry, land-based agriculture, livestock, integrated systems and bioenergy	Mixed employment impact via entrepreneurship development (m/h), use of less labour-intensive technologies in agriculture (m/m); diversification of income sources and access to markets (r/h); additional income to sustainable landscape management (m/h); income concentration (m/m); energy security (resource sufficiency) (m/h); innovative financing mechanisms for sustainable resource management (m/h); technology innovation and transfers (m/m)	Increased food-crops production through integrated systems and sustainable agriculture intensification (r/m); deceased food production (locally) due to large-scale monocultures of non-food crops (r/l); increased cultural habitats and recreational areas via (sustainable) forest management and conservation (m/m); improved human health and animal welfare (e.g., through less use of pesticides, reduced burning practices and agroforestry and silvo-pastoral systems) (m/h); human health impact related to burning practices (in agriculture or bioenergy) (m/m); mixed impacts on gender, intra- and inter-generational equity via participation and fair benefit sharing (r/h) and higher concentration of benefits (m/m)	Mixed impact on ecosystem services via large-scale monocultures (r/h), ecosystem conservation, sustainable agriculture (r/h); increased land use competition (r/m); increased soil quality (r/h); decreased erosion (r/h); increased ecosystem resilience (m/h); albedo and evaporation (r/h)
	Demand side: reduced losses in the food supply chain, changes in human diets and in demand for wood and forestry products			Institutional aspects: mixed impact on tenure and use rights at local level (for indigenous people and local communities) (r/h) and on access to participative mechanisms for land management decisions (r/h); enforcement of existing policies for sustainable resource management (r/h)
Human Settlements and Infrastructure	Compact development and infrastructure	Increased innovation and efficient resource use (r/h); higher rents and property rights (m/m)	Improved health from increased physical activity: see Transport	Preservation of open space (m/m)
	Increased accessibility	Commute savings (r/h)	Improved health from increased physical activity: see Transport; increased social interaction and mental health (m/m)	Improved air quality and reduced ecosystem and health impacts (m/h)

	Mixed land use	Commute savings (r/h); higher rents and property values (m/m)	Improved health from increased physical activity (r/h); social interaction and mental health (l/m)	Improved air quality and reduced ecosystem and health impacts (m/h)