MSc Thesis

Evaluating the GHG reduction potentials of *Project Drawdown*, using integrated assessment model IMAGE

A global and sectoral assessment of 47 mitigation measures that contribute to climate action.

Utrecht University

PBL Netherlands Environmental Assessment Agency

August 11, 2020

Student details

Laura Esmee de Visser
MSc Sustainable Development,
Environmental Change and Ecosystems

+31 (0)6 300 36 901
l.e.devisser@students.uu.nl, or
laura.devisser@pbl.nl

Institutions

Utrecht University, Geosciences
Copernicus Institute of Sustainable Development
Vening Meinesz building
Princetonlaan 8a
3584 CB Utrecht

PBL Netherlands Environmental Assessment Agency
Department of Climate, Air and Energy
Bezuidenhoutseweg 30
2594 AV The Hague

Supervision

Prof. Dr. Detlef van Vuuren
Senior Researcher at PBL Netherlands Environmental
Assessment Agency (The Hague) &
Professor of Integrated Assessment of Global Environmental Change,
Utrecht University (UU)

Dr. Andries Hof
Senior Researcher at PBL Netherlands Environmental
Assessment Agency (The Hague) &
Guest researcher at Copernicus Institute,
Utrecht University (UU)

"*Climate change is the single biggest thing that humans have ever done on this planet. The one thing that needs to be bigger is our movement to stop it.*"

- Bill McKibben

Utrecht University

PBL Netherlands Environmental Assessment Agency

Summary

Global temperatures are rising due to accumulating greenhouse gas concentrations in the atmosphere. Temperatures will continue to rise if additional climate policy's are not implemented. This would lead to irreversible losses of natural systems, affecting human societies as well. Therefore, substantial emission reductions must take place through the implementation of mitigation strategies. Project Drawdown is a study that analysed how to reach the moment of "Drawdown" - the point in time where emissions start to decline. Projection Drawdown provides diverse mitigation options in two possible scenarios (*Scenario 1* and *Scenario 2*). However, it is not clear what methodology was used, and if the study accounted well enough for interactions between mitigation implementations, as well inertias and regional variability. Such dynamics are accounted for in integrated assessment model IMAGE.

During this thesis, IMAGE was used to assess the effectiveness of Project Drawdown's mitigation measures when they are mutually implemented. For this, assessments were done at a global and sectoral scale - including the sectors *electricity*, *transport*, *residential*, *industry* and *non-*CO_2. For each of these sectors, a shortlist was created, including mitigation targets for 2050. The shortlists were collected data from literature and expert knowledge of PBL Netherlands Environmental Assessment Agency. The implementations of these targets resulted in IMAGE scenarios - *Scenario 1* and *Scenario 2*. Moreover, for each sector the net reduction potential in 2050 was calculated for Project Drawdown's mitigation measures, and subtracted from the AMPERE baseline. Using linear interpolation towards 2050, two "Drawdown" scenarios were created.

The results of the IMAGE scenarios and Drawdown scenarios were compared on a global and sectoral scale, together with AMPERE and SSP2 baselines and 2°C scenarios. Global findings of Project Drawdown and IMAGE were relatively similar for *Scenario 1*, reaching emission levels of 59 - 53 GtCO_2-equivalent respectively. However, *Scenario 2* showed a greater difference, with emission levels of 35 - 49.5 GtCO_2-equivalent respectively. Underlying differences were evaluated by means of the sectoral assessments.

For the electricity sector, IMAGE found a greater reduction potential in *Scenario 1* than Project Drawdown, leading to a lower emission level here. IMAGE found a lower reduction potential in *Scenario 2*, and a higher emission level compared to Project Drawdown. In the transport sector, IMAGE found lower reduction potentials than Project Drawdown, and thus higher emission levels in both *Scenario 1* and *Scenario 2*. In the residential sector, IMAGE found lower reduction potentials in *Scenario 1* and *Scenario 2* compared to Project Drawdown, but they reached similar emission levels. For the industry sector, IMAGE found higher reduction potentials and lower emission levels in *Scenario 1* and *Scenario 2*. Lastly, for CH_4 emissions, IMAGE and Project Drawdown found an equal emission level in *Scenario 1*, but *Scenario 2* showed a larger emissions gap between findings of IMAGE and Project Drawdown.

Overall, the findings of the IMAGE model showed that substantial GHG emission reductions could take place with the mitigation measures of Project Drawdown. Generally, IMAGE and Project Drawdown differed slightly in their findings for *Scenario 1*. However, differences between Project Drawdown and IMAGE were often larger for *Scenario 2*, which may be caused by the integration between measures as these were mutually implemented.

Contents

List of Figures

List of Tables

Abbreviations and units

AFOLU	Agriculture, Forestry & Other Land Use
AMPERE	Assessment of climate change Mitigation Pathways and Evaluation of the Robustness of mitigation cost Estimates
CH_4	Methane
CO_2	Carbon dioxide
CO_2-equivalent	Global warming potential of non-CO_2 GHGs, relative to that of CO_2
COP	Coefficient Of Performance
CSP	Concentrated Solar Power
DNE21	Dynamic New Earth 21
E-waste	Electronic waste
F-gas	Fluorinated gas
GCAM	Global Change Analysis Model
GHG	GreenHouse Gas
GISMO	Global Integrated Sustainability MOdel
GLO2	Global Land Outlook
GLOBIO	GLObal BIOdiversity model
GLOFRIS	GLObal Flood RISk
Gt	Gigatonnes
HST	High-Speed Train
IAM	Integrated Assessment Model
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LED	Light Emitting Diode
LDC	Least Developed Country
LPJmL	Lund-Potsdam-Jena managed Land
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MAGNET	Modular Applied GeNeral Equilibrium Tool
N	Nitrogen
N_2O	Nitrous Oxide
n/a	Not available
NDC	Nationally Determined Contribution
P	Phosporus

pkm	Passenger kilometres
ppm	Parts per million
RCP	Representative Concentration Pathway
SCOP	Seasonal Coefficient Of Performance
SSP	Shared Socioeconomic Pathway
TIMER	Targets IMage Energy Regional
W/m^2	Watt per square meter

1 Introduction

In Chapter 1, a concise description is provided about the threat of global warming, and the role of climate policy herein. This introduces the problem definition of our research, and the contribution of this particular research approach. The research is then actualised by similar, recent peer-reviewed studies, eventually leading to the research objectives and research questions.

1.1 The background behind anthropogenic global warming

There is strong scientific consensus that global warming is occurring (Doran and Zimmerman, 2009). The Intergovernmental Panel on Climate Change (IPCC) estimates that it is very likely that human activities increased global temperatures with 1°C above pre-industrial levels (IPCC, 2018). Accumulating greenhouse gases (GHGs) contribute to these warmer temperatures as they increase radiative forcing, resulting in warmer surface temperatures. Today, GHG emissions are still increasing, reaching a record high of more than 50 gigatonnes carbon-dioxide equivalent ($GtCO_2$-equivalent[1]) in 2017 (Olivier et al., 2017).

CO_2 emissions have the greatest contribution to global warming, and are largely the result of an increase in energy consumption and production (figure 1.1) (Stehfest et al., 2014). Other important GHGs are methane (CH_4), nitrous oxide (N_2O) and fluorinated (F) gases - these comprise the "Kyoto gases" together with CO_2 (GHG Protocol, 2014). Many studies have focused on mitigation strategies for energy-related CO_2 emissions, whilst disregarding GHG emissions that originate from other sectors (Van Vuuren et al., 2007).

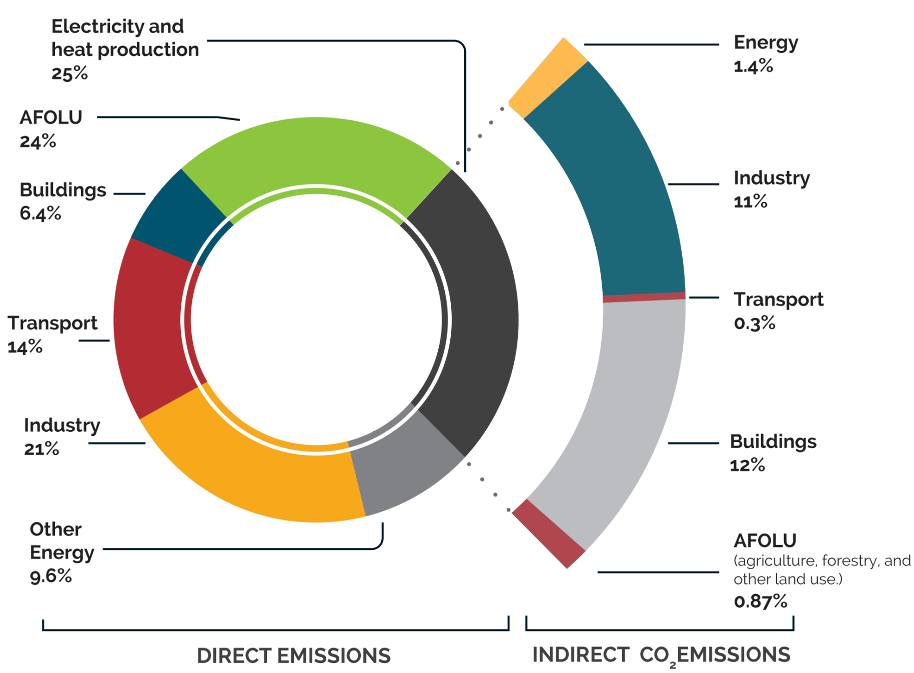

Figure 1.1: Global direct and indirect emissions divided over different economic sectors in 2010. AFOLU stands for agriculture, forestry & other land use (Science Based Targets Initiative, 2014).

[1] Global warming potential of non-CO_2 GHGs, relative to that of CO_2

Climate models show that increasing GHG concentrations in the atmosphere may create further alterations in the climate system, such as increased rainfall intensities or reduced heat uptake by the ocean (Cubasch et al., 2001). Such alterations pose risks to natural systems (e.g. degradation of warm water corals) as well as to human systems (e.g. lower crop yields). Systems can indirectly affect each other through feedbacks that exist between them (Mayer and Rietkerk, 2004). Global warming is considered to be one of the biggest threats to sustainability today.

Without implementing any additional climate policy responses to reduce emissions, global temperatures in 2100 are estimated to reach 3.7 - 4.3°C relative to pre-industrial levels (IPCC, 2014). Surpassing 1.5 - 2°C could lead to irreversible loss of natural systems and human society (IPCC, 2018). Therefore, almost 200 countries signed the Paris Agreement, where the objective is to keep global temperatures below 2°C or even 1.5°C. This needs to be achieved by "reaching global peaking of greenhouse gas emissions as soon as possible" and by "undertaking rapid reductions thereafter in accordance with best available science" (UNFCCC, 2015). Countries submitted their Nationally Determined Contributions (NDCs) which indicate their pledges for reducing GHG emissions (Roelfsema et al., 2018). However, NDCs are considered to be insufficient to achieve the goals to keep temperature increase below 2°C or 1.5°C.

1.2 Problem definition: regarding climate mitigation strategies

Substantial emission reductions must take place in order to stabilize GHG concentrations at low levels (Van Vuuren et al., 2007) and can be achieved through the implementation of climate mitigation strategies that transform current practices in human society (Clarke et al., 2015). To assess the effectiveness of such mitigation measures, researches aim to calculate global GHG emission reduction potentials. One well-known study called *Project Drawdown* analysed how to reach the moment of Drawdown, which is defined as "the future point in time when levels of greenhouse gases in the atmosphere stop climbing and start to steadily decline" (Frischmann et al., 2020). The study finds a cumulative reduction potential of 997 - 1576 $GtCO_2$-equivalent over 2020-2050 through ca. 80 mitigation measures (provided in Appendix 7.1, based on Project Drawdown). This indicates a net reduction of 67 - 106 $GtCO_2$-equivalent in 2050 (see Chapter 3), and is based on two mitigation scenarios:

- *Scenario 1* is ambitious compared to today's policies on climate action, leading to a net emission reduction of 67 $GtCO_2$-equivalent in 2050. This scenario does not reach the moment of Drawdown before 2050. CO_2-equivalent concentrations in the atmosphere would reach 540 ppm in 2050, causing 1.85 °C warming at the end of the century (Frischmann et al., 2020). Drawdown compares *Scenario 1* with the 2°C climate target of the Paris Agreement.

- *Scenario 2* is more ambitious due to faster adoption of robust climate policies, leading to a net emission reduction of 106 $GtCO_2$-equivalent in 2050. *Scenario 2* reaches the moment of Drawdown before 2050. CO_2-equivalent concentrations would reach 485 ppm in 2050, already following a declining path, and cause a peak warming of 1.52 °C in 2050 (Frischmann et al., 2020). Drawdown compares this with the 1.5°C climate target of the Paris Agreement.

Scenario 1 and *2* are compared to the baseline scenario of the AMPERE project. Here, no new climate policies are introduced in the future, leading to rising emissions and global temperatures similar to historic trends (Frischmann et al., 2020; European Union, 2014). The measures cover many sectors, of which *electricity*, *land sinks*, *food, agriculture & land use*, *industry* and *buildings* have the largest potentials for emission reduction (figure 1.2). Project Drawdown is considered to be "the most comprehensive plan ever proposed to reverse global warming" (Hawken et al., 2017).

However, the methodological approach behind Project Drawdown remains rather undiscussed. As this defines the anticipated effectiveness of Drawdown's mitigation strategies, this lack of clarity has not gone unnoticed (Duchin, 2017). Fortunately, Drawdown recognises that it remains a "learning organisation" and states that their study is "a means to add, amend, correct and extend" its information. The aim of our research is to evaluate the mitigation strategy of Project Drawdown, using an integrated assessment modelling approach that provides insights in assumptions.

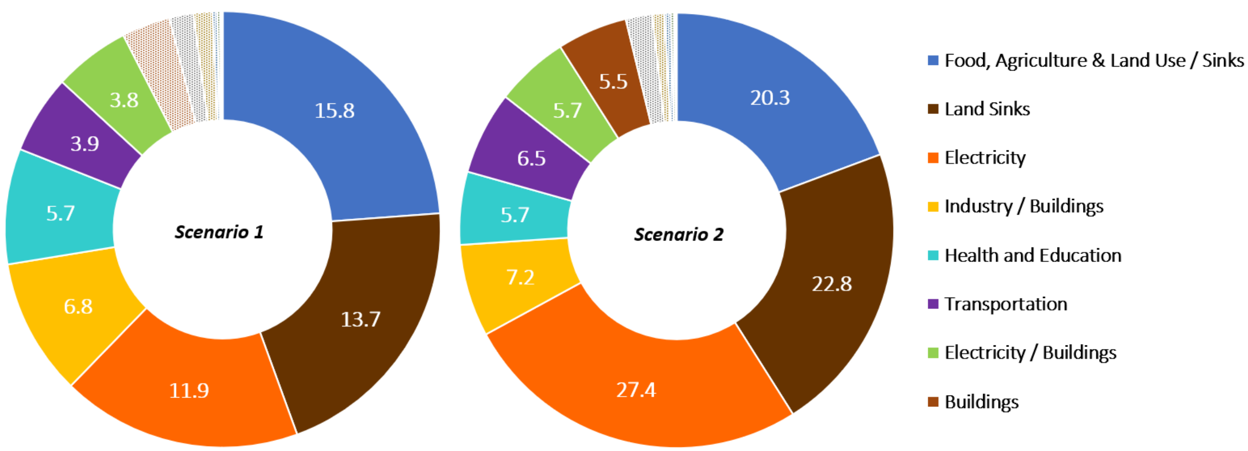

Figure 1.2: Net GHG emission reduction potentials per sector ($GtCO_2$-equivalent) in 2050, based on Project Drawdown. Sectors with a reduction potential < 3 $GtCO_2$-equivalent are not considered in this figure (dotted areas).

1.3 The contribution of integrated assessment modelling

There are multiple factors that complicate the evaluation of mitigation measures and their effectiveness. Insufficient insights in these factors can result in inappropriate or incomplete climate action. One example is that interactions may emerge between mitigation implementations, a phenomenon that can be observed in the case of biofuels (Bentivoglio and Rasetti, 2015). Biofuels are considered to be carbon neutral, and can replace unsustainable fossil fuels. However, concerns exist about interactions between biofuels and foods, as the production of biofuels may lead to increased food prices (Bentivoglio and Rasetti, 2015).

Another example is the inertia of climate responses after the implementation of mitigation strategies. Inertias can be as long as multiple decades and are very uncertain (Trenberth et al., 2016; Van Vuuren and Stehfest, 2013). Even when starting a global mitigation strategy today, a high probability remains of overshooting the 2°C target within this millennium (Friedlingstein et al., 2011). In this way, inertias delay policy responses and slow the progress of climate mitigation.

Lastly, there is much regional variation regarding GHG emissions and climate impacts (Lamarque et al., 2011). Six main emitters are the United States, China, India, Russia, Japan and Europe - which are almost all considered developed countries (Olivier and Peters, 2019). Meanwhile, many least developed countries (LDCs) and developing countries account for much lower emissions, but are most vulnerable to global warming (Ludwig et al., 2007).

A method that can provide information on mitigation options whilst accounting for the dynamics described above, is by using integrated assessment models (IAMs) (Van Vuuren et al., 2007). IAMs are designed to address the link between human development and the environment (Stehfest et al., 2014). This link describes functional relationships, such as the supply of food, water or energy (ibid). IAMs can assess the driving forces behind various systems (i.e. air quality, depletion of fossil fuels) as well as their impacts on these systems. With IAMs, scenarios or pathways can be constructed in the context of climate mitigation, by exploring a variety of socioeconomic developments (Kriegler et al., 2014). The Integrated Model to Assess the Global Environment 3.0 (IMAGE 3.0, hereafter: IMAGE) is particularly focused on GHG emissions. The model is very detailed and accounts for long-term effects, and is therefore widely used in mitigation studies (Van Vuuren et al., 2018; Roelfsema et al., 2018; Blok et al., 2020). IMAGE will play a key role in this research, and will be further described in Chapter 2.

1.4 Previous mitigation studies that used IAMs

Roelfsema et al. (2018) calculated reduction potentials for 2030 if countries would implement sectoral climate policies that have proven successful elsewhere. This "good practice policies scenario" included *renewable electricity*, *oil & gas*, *industry*, *fluorinated gases (F-gases)*, *buildings*, *fuel efficiency*, *electric cars* and reduced *deforestation* (Roelfsema et al., 2018). Integrated assessment results showed a reduction potential of 10 $GtCO_2$-equivalent in the good policies scenario compared to the current policies scenario (60 $GtCO_2$-equivalent emissions in 2030). Their research was a comprehensive version of one conducted by Sitra Studies (2015), who found a reduction potential of 12 $GtCO_2$-equivalent without using an IAM (Sitra Studies, 2015). Blok et al. (2020) provided reduction potentials for 2030 using IAMs, including the sectors *energy production & conversion*, *transport*, *buildings*, *agriculture*, *forestry* and *industry* (Blok et al., 2020). Here, an emission reduction potential was found of 33 $GtCO_2$-equivalent compared to the baseline scenario (61 $GtCO_2$-equivalent).

These researches emphasize that multiple alternative pathways can be feasible, but that it depends on the options for mitigation that are included (Van Vuuren et al., 2018; Roelfsema et al., 2018; Blok et al., 2020). This is influenced by both societal and technological factors, and differs per region. Drawdown increases flexibility through the variety of mitigation options, but variability in technological and social feasibility may be insufficiently addressed. By assessing Project Drawdown's approach in an integrated manner, new insights can be provided on feasible emission reductions. This scientific substantiation can be used to steer developments towards a sustainable pathway.

1.5 Objectives and research questions

The research objective is twofold: firstly, to supplement Project Drawdown with integrated assessment results on said dynamics, and the impacts hereof on the reduction potential. Secondly, to gain insights on whether assumptions and technologies in the IMAGE model can be expanded using the diverse mitigation options of Project Drawdown. The research aims to answer the main research question:

What can an integrated assessment modelling approach in IMAGE tell us about Project Drawdown's mitigation strategy and global emission reduction potential?

The main research question is guided by two sub-questions, to ensure the quality of the research. This concerns a critical evaluation of merging both approaches (Project Drawdown and IMAGE), as well as a sectoral assessment of model outputs before aggregating the data.

How can Project Drawdown's mitigation strategy be adequately implemented in IMAGE?

What are the sectoral reduction potentials of the measures according to IMAGE?

The answer to sub question 1 provides new insights about potential deficiencies of IMAGE, which is part of the research objective. It is expected that the diversity of Project Drawdown can improve IMAGE to some extent. Sub questions 2 and 3, together with the main research question, guide the research to the objective of supplementing Project Drawdown results with insights from sectoral integrated assessment results. New insights are expected to emerge, because different models include varying assumptions, even when only comparing between IAMs (Blok et al., 2020).

2 Theoretical foundation

In Chapter 2, the theoretical foundation of integrated assessment modelling is outlined, introducing well-known emission scenarios called the Representative Concentration Pathways and the Shared Socioeconomic Pathways. Subsequently, the framework of the IMAGE model is explained which will support the understanding of the research method. For further details on the IMAGE framework, see Stehfest et al. (2014).

2.1 Integrated assessment modelling: the basics

Scenarios are used to explore policy options and to assess the feasibility of climate goals, such as the Paris Agreement goal to keep global warming below 2 - 1.5°C (Hare, Brecha & Schaeffer, 2018). Fundamentally, the Representative Concentration Pathways (RCPs) were created, showing the increase in radiative forcing (Watt/m^2) following a certain amount of increase in CO_2 concentrations (figure 2.1) (Van Vuuren et al., 2011, 2014). The RCPs include: one mitigation scenario (RCP2.6), two stabilisation scenarios (RCP4.5 & RCP6.0) and one scenario with high GHG concentrations (RCP8.5). Here, the radiative forcing level of 2.6 W/m^{-2} (RCP2.6) is likely to not exceed the 2°C climate target (IPCC, 2014).

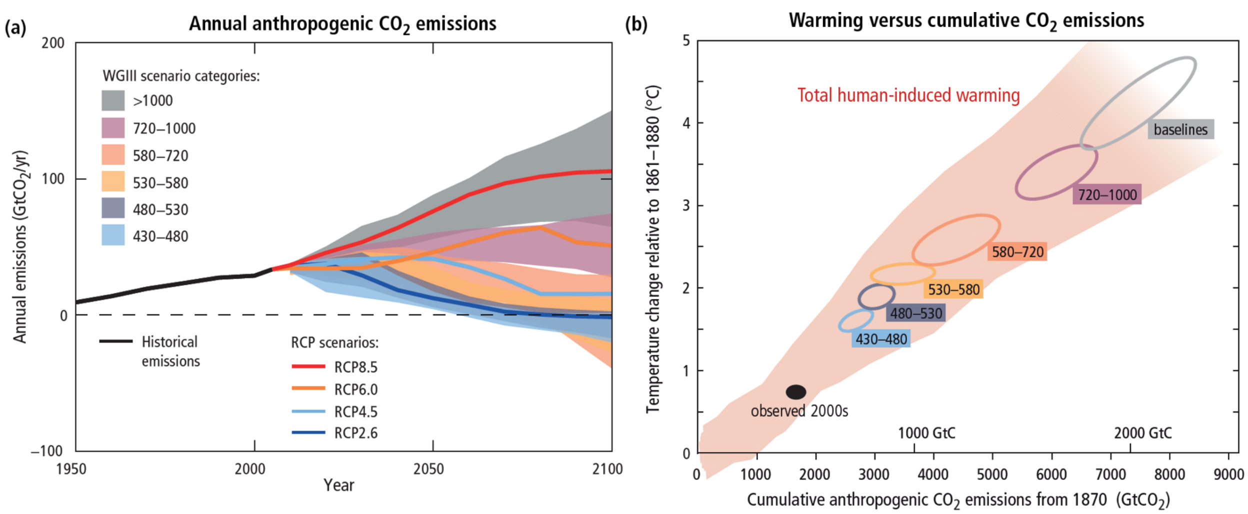

Figure 2.1: (a) Annual anthropogenic (CO_2 emissions $GtCO_2$/yr over 1950 - 2100) for each RCP scenario, provided with corresponding concentrations (b). Warming (°C) relative to 1861 - 1880 versus cumulative CO_2 emissions ($GtCO_2$), provided with corresponding concentrations (IPCC, 2014).

Socio-economic developments determine the feasibility of reaching climate targets. The Shared Socioeconomic Pathways (SSPs) are scenarios and often the starting point of integrated modelling studies, as they represent different levels of socio-economic development. They do not introduce new climate policies and are not affected by climate change in the future (Van Vuuren et al., 2014). Therefore, they are commonly used as hypothetical "reference scenarios" in IAMs. Differences in socioeconomics will result in different emission quantities as well as differences in capacity to implement mitigation measures. Five separate SSPs exist (figure 2.2), each SSP having its own narrative as well as a unique set of quantified measures for development (O'Neill et al., 2014).

SSP1 describes low mitigation and low adaptation challenges; SSP3 has high mitigation and high adaptation challenges; SSP4 describes low mitigation and high adaptation challenges; whereas SSP5 has high mitigation and low adaptation challenges. Finally, SSP2 describes a "middle of the road" pathway (Van Vuuren et al., 2014). For example, SSP3 describes a situation with declining education and technological development, as well as low per capita income and high population growth (Fujimori et al., 2017). This story-line faces high challenges and accelerating climate change, as certain mitigation strategies (e.g. a costly sustainable energy transition) are unattainable. Due to these social challenges, the Paris Agreement acknowledged differences in adaptive capacity between developed and developing countries.

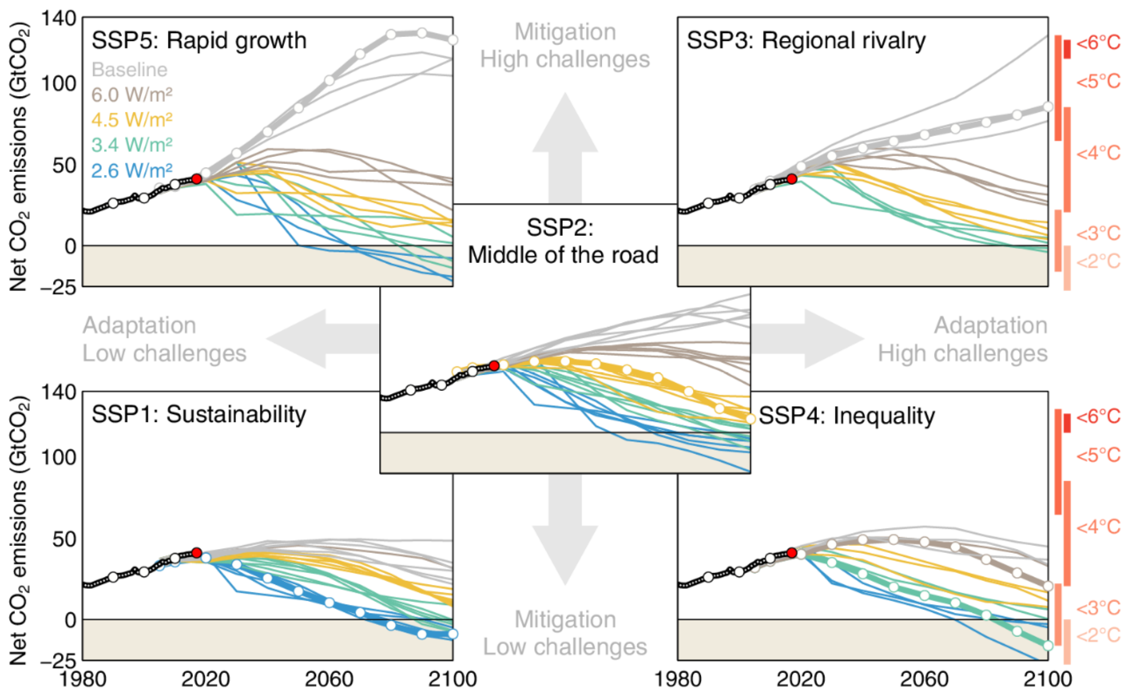

Figure 2.2: The five Shared Socio-economic Pathways, scaled by high mitigation challenges (above), low mitigation challenges (below), high adaptation challenges (right) and low adaptation challenges (left). Colours indicate the forcing level, given in SSP5 (Global Carbon Budget, 2018).

By combining the radiative forcing levels of the RCPs with the SSPs in IAMs, the feasibility of climate goals and the costs for reaching them can be assessed (Hare et al., 2018; Van Vuuren et al., 2014). Namely, achieving lower forcing levels requires higher mitigation challenges for any SSP; but the challenges also depend on the SSP being followed (Van Vuuren et al., 2014). These assessments provide scientific substantiations about reduction potentials, as well as indications for sustainable development in the economic, social and environmental dimensions.

As stated before, IMAGE is particularly focused on GHG emissions, and will be used to model mitigation scenarios in this research. The IMAGE framework is discussed below.

2.2 IMAGE framework

To accurately assess the reduction potentials for the different sectors, the complete IMAGE model will be used and is thus explained in this section. The IMAGE model consists of several sub-systems (figure 2.3). Mitigation measures of Project Drawdown are implemented in the human system, consisting of "agriculture & land use" and "energy supply & demand". These connect directly and indirectly with the Earth system ("land" and "atmosphere & oceans").

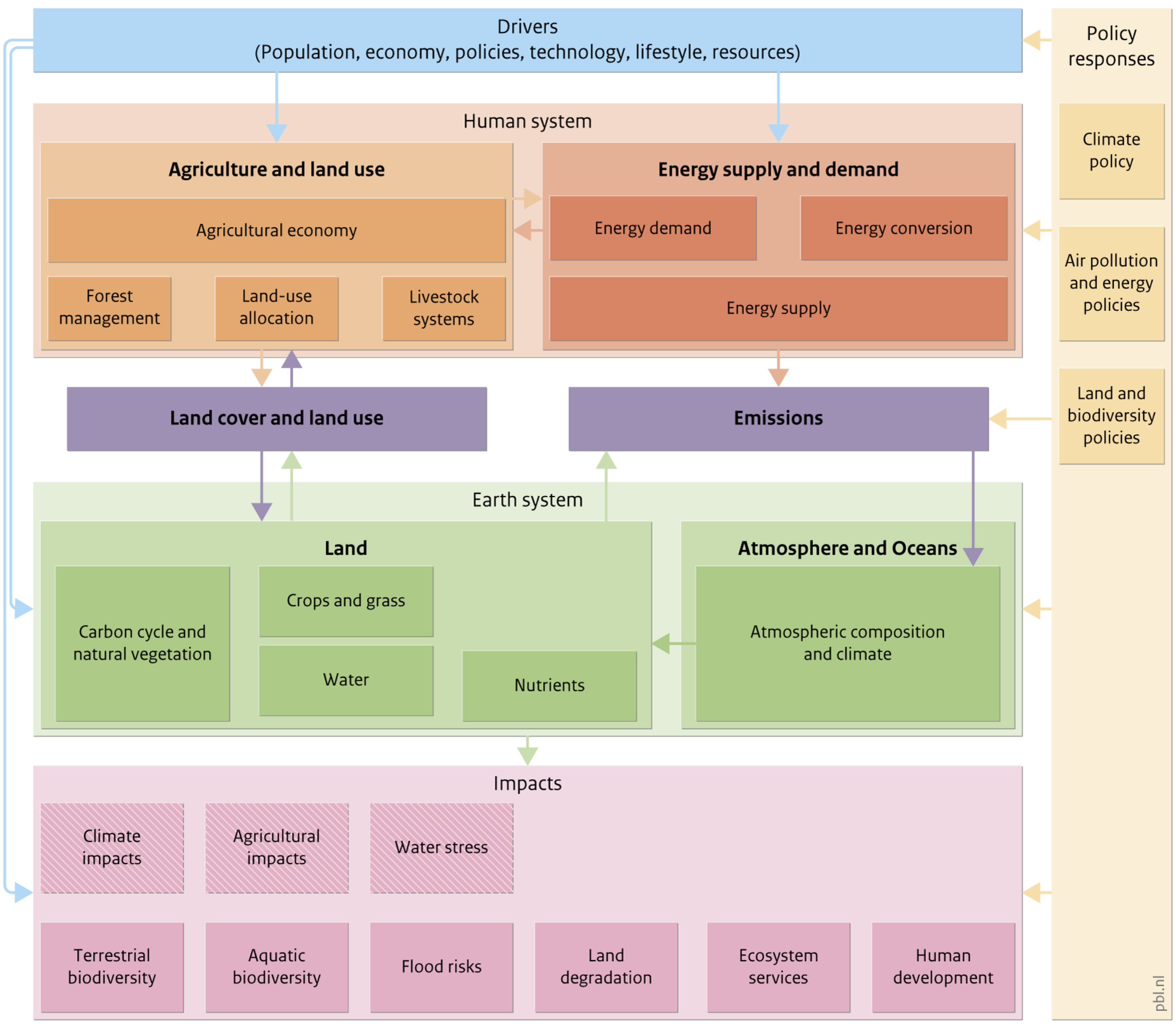

Figure 2.3: The IMAGE framework, consisting of drivers (blue), human system (orange and red), Earth system (green), impacts (pink) and policy responses (beige). Arrows indicate interactions (Stehfest et al., 2014).

2.2.1 Agriculture & land use: IMAGE-land

Within the human system, the IMAGE-land model comprises the modules “agricultural economy”, “forest management”, “land-use allocation” and “livestock systems”. The agricultural economy is mainly driven by demography and income, and is calculated by the MAGNET model. IMAGE-land provides information to MAGNET on land availability and suitability, and on changes in crop yields as a result of climate change. MAGNET includes biofuels (wheat, sugar cane, maize and oilseeds) (Stehfest et al., 2014).

“Forest management” describes the demand for and production of timber, paper and biofuels, amongst others (Stehfest et al., 2014). Three management approaches are included: clear-cutting, selective logging and forest plantations. Trees can only be harvested when forest regrowth has occurred (Stehfest et al., 2014). For “land-use allocation”, crop- and grasslands are abandoned or expanded until demand has been met. Yields can change over time because of technological advances, climatic change and land heterogeneity. When yield is relatively low in a certain area, more agricultural land is needed relative to the production increase. Data is calculated using the carbon, vegetation and water model LPJml (Stehfest et al., 2014).

Finally, “livestock systems” comprises different types of livestock: small ruminants (i.e. sheep), large ruminants (i.e. beef cattle) and monogastrics (i.e. poultry). Five different feedstocks are considered, consisting of grass, feed crops, crop-residues, animal products and scavenging (Stehfest et al., 2014). Energy requirements depend on animal activity and productivity (amongst others).

2.2.2 Energy supply & demand: TIMER

The IMage Energy Regional model (TIMER) comprises the “energy demand”, “energy conversion” and “energy supply” modules in the human system. The “energy demand” module describes how final energy demand is determined for five economic sectors - *transport, residential, industry, public & private services,* and *other* (Stehfest et al., 2014). Demand for energy is driven by population, income and energy intensity, and exists for different energy carriers - such as coal, oil, natural gas, traditional bioenergy, modern bioenergy, hydrogen or electricity. The energy demand per energy carrier is input for the “energy conversion” and “energy supply” modules.

“Energy conversion” describes the conversion of primary sources into secondary energy carriers, which are easily accessible for final consumption (Stehfest et al., 2014). Examples are crude oil conversion into oil products, or electricity generation through renewable technologies. The “energy supply” module describes the production of primary energy carriers, and calculates costs for the primary and secondary energy carriers (Stehfest et al., 2014). Energy conversion depends on investment decisions and the actual use of capacity, while the availability of resources is essential for energy supply.

Generally, in TIMER, an energy or carbon tax is implemented for energy demand and supply. The carbon tax has a significant influence on investments and strategies in the power system, leading to changes in market shares. A carbon tax is, however, not used to implement mitigation measures in the present study, as Project Drawdown did not price carbon due to existing uncertainties (Hawken et al., 2017). Additional factors can be introduced to influence energy supply and demand, such as premium factors that can be added to the price of certain technologies, either to increase or decrease their market share. Other factors are restrictions on fuel trade, or sustainability criteria, influencing the emissions of GHGs and other air pollutants.

2.2.3 Interaction

"Land cover and land use", as well as "emissions", are key linkages between the human system and the Earth system. Human activities affect ecosystem structures and nutrient cycles through housing, agriculture or infrastructure (Stehfest et al., 2014). Vice versa, landscapes can determine whether settlement or agriculture will occur. A main linkage between land cover and GHG emissions through carbon sequestration by vegetation (Lal, 2008). Other environmental impacts due to emissions are acidification, pollution and climate change. In turn, these environmental impacts can influence human behaviour.

2.2.4 Land, atmosphere & oceans

The Earth system consists of submodules "carbon cycle and natural vegetation", "crops and grass", "water", "nutrients" and "atmospheric composition and climate". The productivity of the first and second module are modelled at grid cell level using LPJmL. Key inputs are climate conditions, soil types and technology (Stehfest et al., 2014). Changes in land cover and land use impact the carbon cycle as well as crop and grass productivity.

The "water" submodule is a global hydrology model, including irrigation, water availability, agricultural water demand and water stress. Water demand for agriculture is calculated in LPJmL, whereas for other sectors, water demand is based on drivers such as demography and economy. The "nutrients" submodule covers nitrogen (N) and phosporus (P) from point sources and non-point sources. Driving forces for N and P are fertilisers, populations and wastewater. Surpluses of N and P will enter coastal waters via rivers, but outputs can occur through crop harvesting, grass-cutting and grazing (Stehfest et al., 2014).

Lastly, the "atmospheric composition and climate change" submodule uses emissions of GHGs and air pollutants to derive changes in their respective atmospheric concentrations. Climate change is caused by the global mean temperature change, and calculated using an adapted version of the climate model MAGICC 6.0. Climate change, including temperature and precipitation, is regionally variable and calculated for 0.5x0.5 degree grid cell. Feedbacks relating to climate change are accounted for.

2.2.5 Impacts & policy responses

IMAGE includes various impacts of global environmental change, which are calculated by impact submodels (e.g. GISMO, GLOBIO and GLOFRIS). Projected impacts (e.g. on "human development", "aquatic biodiversity" and "terrestrial biodiversity") can be compared to a baseline, and the discrepancy between these scenarios may reveal policy gaps. Building on this, new policy responses can be implemented.

2.3 Suitability of IMAGE for the present study

Enabling interactions to occur is a key concept of the model, and in doing so, IMAGE is relatively detailed in its analysis (Roelfsema et al., 2018). It represents activity in different sectors in terms of absolute indicators, creating clear-cut interpretations of policies that are implemented. Both the human and Earth system can be run annually, or at 5-year intervals, while focusing on long-term trends to capture inertia of environmental changes. The model can create scenarios up to 2100, and historical data (1971-2015) is used for calibration (Stehfest et al., 2014).

The spatial scale for socioeconomic developments in IMAGE consists 26 different regions (figure 2.4). The regions differ based on their relevance for environmental issues, development issues, and relative coherence within the regions. This gives insight into (i) where local problems occur, (ii) what their driving forces are, and (iii) how changes in certain regions influence other regions, enhancing the assessment of mitigation options (PBL, 2020).

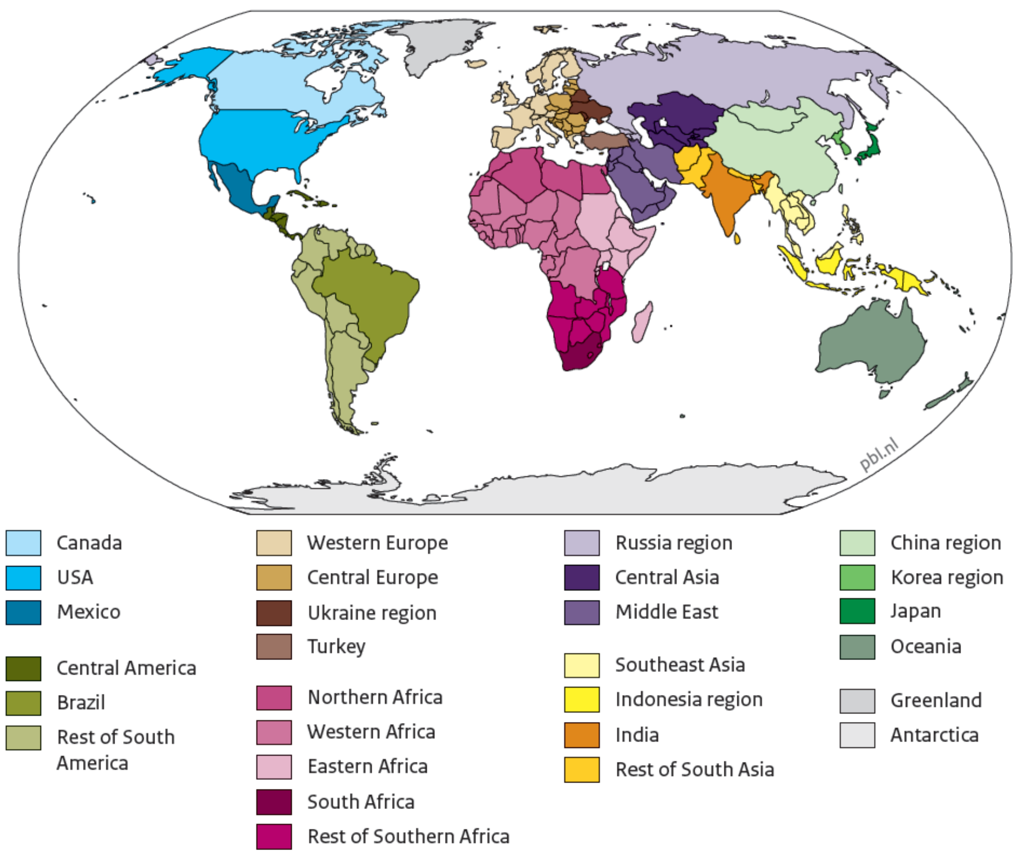

Figure 2.4: The region classification map used in IMAGE, including 26 different world regions (PBL, 2020).

3 Research method

In Chapter 3, the methodological approach of the research is explained. The steps taken for data collection are highlighted, followed by the modelling approach that is used in IMAGE, and subsequent data analysis. Thereafter, sectoral implementations are explained and supplemented with shortlists.

3.1 Data collection for IMAGE implementations

3.1.1 Step 1: Assigning measures to IMAGE sectors

Mitigation measures were implemented individually in IMAGE, whilst the analysis is carried out on global and sectoral scales, to account for integration between measures. For the implementation of measures, data about the individual mitigation measures of Project Drawdown had to be collected. Data collection was based on a series of steps (figure 3.1). Firstly, the Project Drawdown measures were assigned to the appropriate economic sectors of IMAGE. These consist of: *electricity*, *transport*, *residential*, *industry* & *non-CO_2*. The latter sector includes mainly CH_4 emissions (from AFOLU and waste), and F-gas emissions. This categorisation was done so that the different experts at PBL Netherlands Environmental Assessment Agency, which are familiar with the different sectors, could be consulted appropriately.

3.1.2 Step 2: Survey on replicability of measures in IMAGE

Secondly, the experts at PBL Netherlands Environmental Assessment Agency were asked to fill out a survey to assess the replicability of the mitigation measures in IMAGE. The survey consisted of a list of all mitigation measures, which could be classified as being "directly represented", "indirectly represented (proxy)" or "not represented (n/a)" by IMAGE in the current state. For example, the use of *wind turbines* grows in Project Drawdown, and this technology is directly represented in IMAGE. *Health and education*, however, was modelled using SSP1 data as a proxy, with optimistic assumptions on population and education. Drawdown's *biochar* measure is not represented by the model (n/a). During this selection, it was determined whether the measure is on the supply or demand side in the model, to be able to assign the measures to the coherent sub-modules.

3.1.3 Step 3: Translation of Project Drawdown targets

Thirdly, if needed, the Project Drawdown targets were translated to usable data for IMAGE implementation (figure 3.1). The steps 1 - 3 resulted in one shortlist per sector, including (i) the mitigation measures per sector (ii) the replicability of these measures in IMAGE and (iii) the targets have to be reached (generally in 2050) in IMAGE.

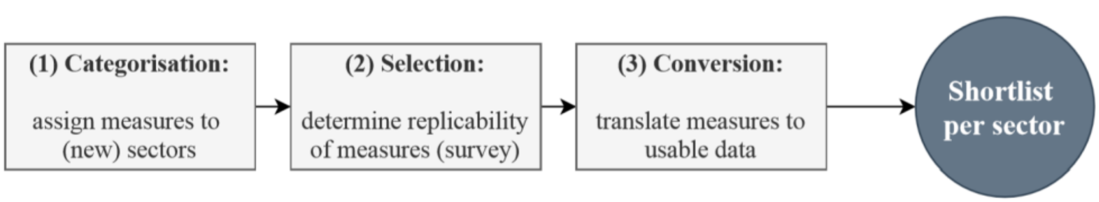

Figure 3.1: Schematic representation of the steps taken for the data collection. The three steps resulted in one shortlist per sector.

3.1.4 Implementing the shortlists in IMAGE

The targets in the shortlists were used to adapt input parameters, which were then included in the input files of the SSP2 baseline (v2017). In this way, SSP2 data was adjusted so that Project Drawdown's suggested targets were met. This resulted in two mitigation scenarios that could be run in IMAGE: *Scenario 1* and *Scenario 2* in $GtCO_2$-equivalent (described in Chapter 1).

3.2 Electricity sector

The modelling approach for the *electricity* sector was either based on (i) the implementation of shares (%) of electricity production per technology, or (ii) assumptions on storage and distribution of electricity (figure 3.2). For electricity production technologies, the fractions determine the electricity generation mix in 2050 (table 1), and were used as input parameters for TIMER. Storage and distribution measures were not explicitly modelled in Project Drawdown due to double-counting and complexity issues (Project Drawdown, 2020v,l).

It is assumed that the electricity supply technologies are clear-cut, thus a detailed description of these measures are not provided in this section. Definitions can be found in Appendix A or on the website of Project Drawdown (Project Drawdown, 2020f). 15 measures were identified for the electricity sector, in the energy supply module (table 1). Generally, the Project Drawdown targets were directly implemented in TIMER.

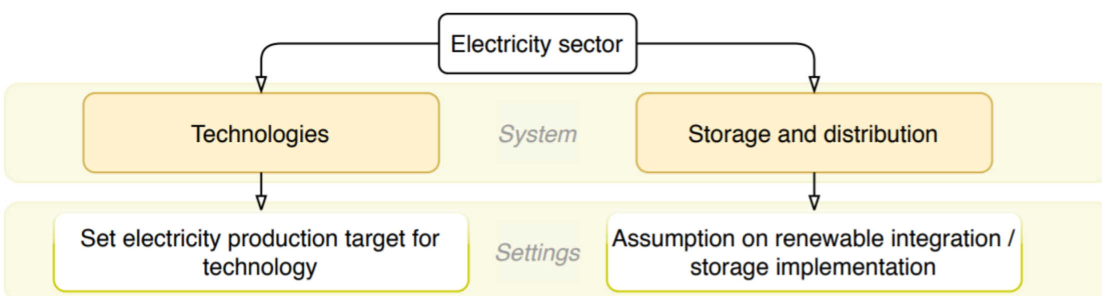

Figure 3.2: A schematic overview of the modelling approach in the electricity sector.

Onshore wind turbines and *offshore wind turbines* were individually modelled in TIMER, using the production shares that are used in Project Drawdown for 2050 (table 1). *Micro wind turbines*, however, were not available in TIMER - the share of this technology was added to that of *onshore wind turbines*. Hence, this measure was modelled through a proxy. *Distributed solar photovoltaics*, *utility-scale solar photovoltaics* and *concentrated solar power* all cover solar-powered renewables, and were modelled separately as well based on their electricity production shares (table 1).

Geothermal power accounts for a large share of a category "other renewables" in TIMER. Hence, this measure is modelled through a proxy, as the share was applied for this category of "other renewables". *Nuclear power* was directly implemented based on its share (table 1). Ocean power (or: wave power) can be modelled directly as well. However, *small hydropower* is part of "total hydropower" in TIMER. *Small hydropower* is thus modelled through a proxy, where the SSP2 baseline assumptions were used for total hydropower in both *Scenario 1* and *Scenario 2*. For *biomass power* and *waste-to-energy* Project Drawdown expected relatively low shares for electricity production in 2050 compared to the SSP2 baseline scenario. Therefore, SSP2 baseline assumptions were used for these measures as well.

3.2.1 Regional scaling

Electricity production is regionally determined in TIMER. A "maxtax" run (allowing a common carbon tax climate policy) provided output data of electricity production for all 26 regions. This data was only used to scale Project Drawdown's global electricity production shares per technology, based on the relative differences in electricity production between regions. An example of these calculations is given:

Region A: 10 GJ, 5% distributed solar PV (0.5 GJ)
Region B: 5 GJ, 15% distributed solar PV (0.75 GJ)

Target region A + B = 10% (1.5 GJ)
*Target region A: 6% (1.5 * 0.5 / (0.5 + 0.75))*
*Target region B: 18% (1.5 * 0.75 / (0.5 + 0.75))*

Distributed energy storage, *utility-scale energy storage*, *grid flexibility* and *microgrids* were all not explicitly modelled in Project Drawdown. The first three measures, however, were separately implemented in TIMER, where one could choose between pessimistic, standard or optimistic settings for the storage and distribution. Standard settings were used for *Scenario 1*; optimistic settings for *Scenario 2*.

Table 1: Electricity shortlist including mitigation measures of Project Drawdown, the manner in which they were modelled, and the appropriate targets for 2050. Left arrows indicate that no translation occurred for implementation in IMAGE. A range is presented for Scenario 1-Scenario 2 consistently.

Measure	**Modelled**	**Mitigation target (2050)**	
		Project Drawdown	**IMAGE run**
Onshore wind turbines	Directly	19.6-26.9% of electricity production	←
Offshore wind turbines	Directly	4.2-3.2% of electricity production	←
Micro wind turbines	Proxy	0.04% of electricity production	←
Distributed solar PV	Directly	13.5-14.2% of electricity production	←
Utility-scale solar PV	Directly	20.3-25% of electricity production	←
Concentrated solar power	Directly	5.9-7.3% of electricity production	←
Geothermal power	Proxy	2.6-2.8% of electricity production	←
Nuclear power	Directly	12.2-8.6% of electricity production	←
Ocean power	Directly	0.86% and 520 TWh of electricity production	0.86-1.12% of electricity production
Small hydropower	Proxy	994-1136 TWh produced	SSP2 hydropower assumptions
Biomass power	Directly	1.1-0.86% of electricity production	SSP2 biomass assumptions
Waste-to-energy	Directly	1.1-0.3% of electricity production	SSP2 waste-to-energy assumptions
Distributed energy storage	Proxy	Not explicitly modelled	standard & optimistic settings
Utility-scale energy storage	Proxy	Not explicitly modelled	standard & optimistic settings
Grid flexibility	Proxy	Not explicitly modelled	standard & optimistic settings
Microgrids	-	Not explicitly modelled	-

3.3 Transport sector

In the *transport* sector, targets were often described very exact. To adequately implement these targets in TIMER, it was determined whether (i) the measure addressed passenger travel or freight transport, and (ii) whether the measure addressed a mode share or a vehicle (technology) share within a mode. This lead to a consistent modelling approach in this sector (figure 3.3). Measures addressing the usage of modes were conversed to the amount of total passenger kilometers (pkm) in 2050. On the other hand, measures describing a vehicle (technology) share, which indicate efficiency gains within a certain mode, were converted to the share (%) of the technology within the mode (if needed). 15 Project Drawdown measures were identified for the transport sector in the energy demand module (table 2).

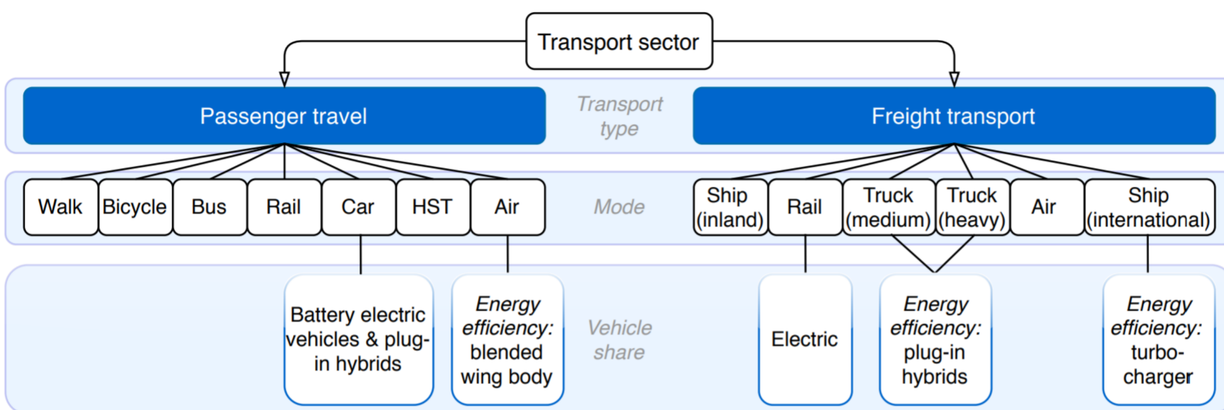

Figure 3.3: A schematic overview of the modelling approach in the transport sector.

The measure *electric cars* entails a vehicle share of battery electric vehicles of the total car fleet in 2050. For this measure, Drawdown provided the absolute numbers of the amount electric cars, as well as the share of total pkm accounted to electric cars (Project Drawdown, 2020j). This pkm share was applied to the total share of the car mode of SSP2 data in 2050, and resulted in the target for *electric cars* as indicated in table 2. *Hybrid cars* entails a vehicle share of plug-in hybrid electric vehicles. This measure was not provided with the share of total pkm's in 2050. Hence, the same ratio between the absolute numbers of cars and pkm as applied to *electric cars* by Drawdown, was applied to *hybrid cars*. Again, this share was applied to the share of the total car mode, resulting in the target provided in table 2.

Public transit comprises mass transit options (e.g. bus, metro, tram) excluding non-motorized vehicles, to travel around cities (Project Drawdown, 2020r). The concept of public transit is not directly available in TIMER, and therefore, bus and train shares were adapted instead. Drawdown indicated the current adoption of public transit, and provided the targets for 2050 (Project Drawdown, 2020r). This relative change in adoption of public transit was applied to SSP2 data, resulting in the targets indicated in table 2.

Both *walkable cities* and *bicycle infrastructure* address the design of urban environments in order to encourage walking or cycling. TIMER does not allow for changes in the design of urban environment, hence these measures are modelled through a proxy of increased mode shares of walking and cycling. For *walkable cities*, the amount of billion pkm's provided by Drawdown were applied to the total pkm's of SSP2 data in 2050, leading to the share presented in table 2. For *bicycle infrastructure* the same approach was used - the amount of pkm's accounted to cycling were applied to the total pkm's of SSP2 data in 2050, leading to the share presented in table 2.

Telepresence partly replaces business air travel, by introducing the possibility to join business meetings and other collaborations online (Project Drawdown, 2020u). The concept of telepresence is not available in TIMER, and was modelled through a proxy of reduced travel demand in the air mode. For this, it is assumed that business air travel covers ca. 20% of total air travel (NCHRP, 2012; Investopedia, 2019), providing the reduction in total air travel demand (table 2). *Efficient aviation* describes the increased use of technologies to make passenger air crafts 15-20% more efficient (e.g. through fuel-efficient engines, wingtip devices, lighter weight) (Project Drawdown, 2020g). In TIMER, blended wingbody air crafts are introduced as vehicle types, as these have a similar energy efficiency increase in TIMER.

High-speed rail scenarios assume the same growth in global track length, but different levels of usage of (existing) tracks (Project Drawdown, 2020o). Drawdown indicated the current adoption of high-speed rail and provided the targets for 2050 (Project Drawdown, 2020o). The relative change in adoption of high-speed rail was applied to SSP2 data, resulting in the targets indicated in table 2. The increased usage is modelled by increasing the load factors using reduced income elasticity - with higher incomes, higher loadfactors emerge. Load factors are also used for *carpooling*, or ridesharing, which increases car occupancy and thus reduces the amount of cars on the roads (Project Drawdown, 2020d). Again, the load factors are elevated through reduced income elasticity. Drawdown's targets are reached by iteratively changing the income elasticity until the load factors were correct in TIMER.

Electric trains is a measure that covers the increased electrification of freight railways (Project Drawdown, 2020k), which is modelled through adapting the vehicle share of electric trains. Similar to the *high-speed rail* measure, increased usage of the rails is modelled through increased load factors. *Efficient ocean shipping* uses technologies to make maritime shipping less fuel-intensive (e.g. through technical improvements, operational changes or fuel replacement) (Project Drawdown, 2020h). To make ships adequately more efficient, turbochargers are increased as these have a similar energy efficiency increase in TIMER. *Efficient trucks* describes an increase in the usage of fuel reduction technologies for freight trucks, reaching an efficiency gain of 40% (Project Drawdown, 2020i). Plug-in trucks are used in TIMER due to a similar energy efficiency increase.

Finally, the measure *electric bicycles* is excluded as this concept not available in TIMER in the current state of the model.

Table 2: Transport shortlist including mitigation measures of Project Drawdown, the manner in which they were modelled, and the appropriate targets for 2050. Left arrows indicate that no translation occurred for implementation in IMAGE. A range is presented for Scenario 1-Scenario 2 consistently.

Measure	**Modelled**	**Mitigation target (2050)**	
		Project Drawdown	**IMAGE run**
Electric cars	Directly	0.86-1.2 bln electric cars on the road	40-57.5% of cars electric
Hybrid cars	Directly	621-236 mln hybrids on the road	30-10% of cars hybrid
Public transit	Proxy	22-35% adoption of public transit	7.4-12% of total pkm
Walkable cities	Proxy	2,589-4,290 bln pkm on foot	12-20% of total pkm
Bicycle infrastructure	Proxy	3.4-6 tln pkm by bike	9-16% of total pkm
Telepresence	Proxy	Business air travel reduced by 16-30%	Reduced air travel demand (3.2-6%)
Efficient aviation	Directly	80-85% of air crafts efficient	←
High-speed rail	Directly	81.000 km of track + incr. use	1.4% of total pkm + incr. use
Carpooling	Directly	Load factor reaches 1.75-2	←
Electric trains	Directly	89-40% of rail electric + incr. use	←
Efficient ocean shipping	Directly	57-78% of ships efficient	←
Efficient trucks	Directly	50-100% of trucks efficient	←
Electric bicycles	n/a	n/a	n/a

3.4 Residential sector

In this sector, it was not always possible to "dictate" the share of a given technology. In TIMER, technologies compete with each other for a market share, based on their relative costs (Stehfest et al., 2014). In the present study, this competition was influenced by adapting a parameter which was added to the price - called a premium factor (see Chapter 2). Thus, by making a certain technology more expensive, it reaches a lower market share (and vice-versa). Other than premium factors, existing input files were adapted directly, or new input files were created and added to the scenario runs (figure 3.4).

For the residential sector, 13 measures were identified in both the energy demand and the energy supply modules. The targets addressed by premium factors (table 3) were established through an iterative process of adapting the premium factors (until the targets were met).

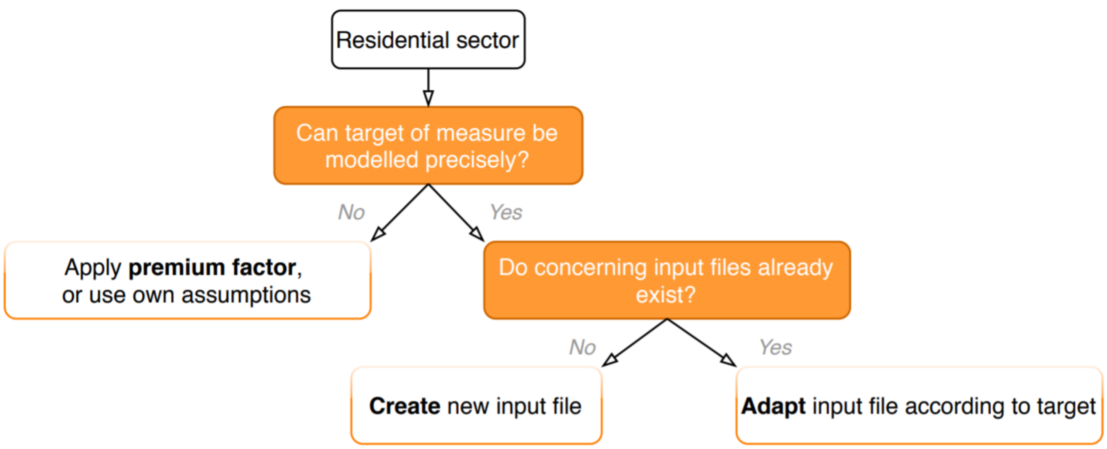

Figure 3.4: A schematic overview of the modelling approach in the residential sector.

Smart thermostats reduce heating and cooling demands of households, saving 10 - 15% of energy needs (Project Drawdown, 2020t). The 15% in energy savings was applied to the adoption rates of *smart thermostats*, which lead to a new demand for space heating (table 3). *Insulation*, *dynamic glass* and *high-performance glass* were modelled together. Instead of implementing the annual retrofit rate in TIMER, insulation levels were increased. There are six insulation levels (1 = lowest insulation level; 6 = highest insulation level). By implementing a premium factor, insulation level 4 and 5 were implemented for *Scenario 1* and *Scenario 2* respectively.

District heating, which is a supply measure, is a renewably-powered network of insulated pipes, that satisfies the space heating demand (Project Drawdown, 2020e). In TIMER, a premium factor is used to promote this heating technology. *High-efficiency heat pumps* use the latent heat from the environment, replacing appliances such as heaters and air-conditioners (Project Drawdown, 2020n). For this measure, a Seasonal Coefficient of Performance (SCOP) is provided by Drawdown. In TIMER, Coefficients of Performance (COP) were implemented, differing slightly from SCOP by not accounting for seasonal influences (Roestenberg, 2015). Therefore, the SSP2 baseline assumption where COP = 3.9 was used for *Scenario 1*. The Project Drawdown target was, however, used for *Scenario 2*.

Low-flow fixtures save water and, simultaneously, energy for water heating. This measure was modelled through reduced water heating demand based on the targets in table 3. This measure was also coupled with an existing "shower less" measure, which reduces water use. The use of *LED lighting* is assumed to increase greatly in 2050 (table 3). In TIMER, incandescent lighting is fully replaced by LED in 2060 (*Scenario 1*) and in 2050 (*Scenario 2*).

Building retrofitting is not explicitly modelled in Project Drawdown, due to double counting issues (Project Drawdown, 2020c). Therefore, this measure is excluded from the analysis. Due to complexity issues in the present study, *water distribution efficiency* is also excluded from this analysis.

Table 3: Residential shortlist including mitigation measures of Project Drawdown, the manner in which they were modelled, and the appropriate targets for 2050. Left arrows indicate that no translation occurred for implementation in IMAGE. A range is presented for Scenario 1-Scenario 2 consistently.

Measure	**Modelled**	**Mitigation target (2050)**	
		Project Drawdown	**IMAGE run**
Smart thermostats	Proxy	58-63% adoption	Reduced space heating demand (8.7-9.5%)
Insulation	Directly	1.6-2% annual retrofit rate	Increased insulation levels (premium factors)
Dynamic glass	Proxy	200-341 mln m^2 installed	Increased insulation levels (premium factors)
High-performance glass	Proxy	2.75-5% annual retrofit rate	Increased insulation levels (premium factors)
District heating	Directly	13-20% of building space heat (renewably powered)	← (premium factors)
High-efficiency heat pumps	Directly	SCOP reaches 3.5-3.9	COP reaches 3.9-4.3
Solar hot water	Proxy	Provides 15-30% heated water	Reduced water heating demand (15-30)%
Low-flow fixtures	Proxy	65-80% adoption	Reduced water heating demand (6.5-8%)
LED Lighting	Directly	85-92.5% LED adoption	100% LED adoption in 2060-2050
Building automation systems	n/a	n/a	n/a
Green & cool roofs	n/a	n/a	n/a
Building retrofitting	-	Not explicitly modelled	-

3.5 Industry sector

The measures in the *industry* sector mainly addressed alternative material sources, and the recovery of used materials for recycling. 4 measures were identified for the industry sector, in the energy demand module (table 4). The measures were generally directly available in TIMER.

Recycling describes the increase in the recovery of recyclable materials (metals, glass, plastics, and others including e-waste, ceramics, rubbers and textiles) (Project Drawdown, 2020s). The general recycling rate grows to 65-68% of the market in 2050 (table 4). However, this target could not be implemented in TIMER, as recycling is divided in different sectors here. Important TIMER sectors for recycling are steel and chemicals (plastics). Steel and plastics were therefore used as a proxy for the general recycling measure. For steel, recycling rates were assumed to increase to a maximum of 85% in *Scenario 2*, which is equal to SSP1 data. For *Scenario 1*, the median between the current rate (70%) and maximum rate (85%) was applied globally. For plastics recycling, an existing data file was used to enable that 30% of plastics go back to feedstock (*Scenario 1*) and 70% of plastics go back to feedstock (*Scenario 2*).

Paper materials are excluded from the measure described above, as *recycled paper* is a separate measure. Here, the Project Drawdown target for paper recycling was directly applied in TIMER (table 4). *Alternative cement* is the (partial) replacement of clinker in conventional cement, with more sustainable materials (Project Drawdown, 2020a). Project Drawdown assumes reduced clinker ratios in 2050. In TIMER, clinker ratios were applied for this measure. *Bioplastics* replace petroleum-based plastics with biomass-based materials (Project Drawdown, 2020b). In order to reach this target, a premium factor was applied to promote bioplastics.

Table 4: Industry shortlist including mitigation measures of Project Drawdown, the manner in which they were modelled, and the appropriate targets for 2050. Left arrows indicate that no translation occurred for implementation in IMAGE. A range is presented for Scenario 1-Scenario 2 consistently.

Measure	Modelled	Mitigation target (2050)	
		Project Drawdown	**IMAGE run**
Recycling	Proxy	65-68% recycling rate	77.5-85% (steel) & 30-70% (plastic) recycling rate
Recycled paper	Directly	69-74% recycling rate	←
Alternative cement	Directly	0.61-0.46 clinker to cement ratio	←
Bioplastics	Directly	12-46% of total plastics market	← (premium factors)

3.6 Non-CO_2 sector

For the *non-CO_2* sector, 7 measures were identified that explicitly addressed other GHGs, specifically methane (CH_4) and F-gases (table 5).

The measures *improved clean cookstoves* as well as *biogas for cooking* are cooking measures, which are originally assigned to the residential sector in TIMER. However, due to the contribution of CH_4, these measures were assigned to this non-CO_2 sector. *Improved clean cookstoves* replace traditional cookstoves that burn wood, charcoal, animal dung and crop residues inefficiently, by solar-powered or fuel-powered cookstoves (Project Drawdown, 2020p). *Biogas for cooking* replaces fuels through the anaerobic digestion of organic waste (thus, acting like small methane digesters).

For *improved clean cookstoves Scenario 1*, a premium factor was applied to make clean cookstoves increasingly accessible. The Project Drawdown target was reached through an iterative process of adapting the premium factor until the target was reached. For *Scenario 2*, traditional biofuels and coal were made unavailable in an existing input file, following Drawdown's description. Additionally, kerosene is also made unavailable as this is considered a "dirty fuel" by the United Nations (UN, 2019). For *biogas for cooking*, modern biofuels were promoted in TIMER through a premium factor as well, automatically influencing the use of modern biofuels for *improved clean cookstoves* as well.

Methane digesters centralise organic wastes in tanks, which can be used to control the decomposition of that waste (Project Drawdown, 2020q). This reduces CH_4 emissions, and simultaneously, provides a new type of biofuel for electricity generation, replacing other fuels. Reductions of CH_4 were estimated, and implemented in IMAGE, and the provision of electricity is modelled through reduced electricity demand. *Landfill methane capture* and *composting* are other important CH_4 measures. For *landfill methane capture* it is assumed that a 90% collection efficiency can be reached, while CH_4 reduction due to composting reaches 50% (M. Harmsen, pers. comm., July 2020). This lead to the targets as identified in table 5. The adoption of both measures together, are estimated to reach 57 - 24% reduction in CH_4 emissions.

Alternative refrigerants replaces a large fraction of HFC refrigerants. For the present study, it is assumed that approximately 93% of HFCs are commonly used as refrigerants (Enviros, 2012). The concept of *refrigerant management* is not available in TIMER, and is excluded from this analysis.

Table 5: Non-CO_2 shortlist including mitigation measures of Project Drawdown, the manner in which they were modelled, and the appropriate targets for 2050. Left arrows indicate that no translation occurred for implementation in IMAGE. A range is presented for Scenario 1-Scenario 2 consistently.

Measure	**Modelled**	**Mitigation target (2050)**	
		Project Drawdown	**IMAGE run**
Improved clean cookstoves	Directly	Access for 84-100% of households (2030)	← (premium factor *Scenario 1*)
Biogas for cooking	Proxy	Replaces 57-87 mln unfit stoves, reduces CH_4 & N_2O	← (premium factors)
Methane digesters	Proxy	1.7-0.07% of electricity production, reduces CH_4 & N_2O emissions	←
Landfill methane capture	Directly	Adoption reaches 70-0%	Adoption reaches 70-5%
Composting	Directly	Adoption reaches 48-60%	←
Alternative refrigerants	Directly	Replaces 67-82% of HFC refrigerants	Replaces 66-76% of total HFCs
Refrigerant management	n/a	n/a	n/a

3.7 Health & education

One remaining measure is *health and education.* This mitigation measure covers the concepts “education for girls” and “family planning” around the world (Project Drawdown, 2020m). The measure underlies all other sectors as it slows population growth, which is an important driver in IMAGE. The measure is modelled using SSP1 population data (table 6). For this measure, no differences exist between *Scenario 1* and *2*.

Table 6: Health & education shortlist including the mitigation measure of Project Drawdown, the manner in which it was modelled, and the appropriate targets for 2050.

Measure	**Modelled**	**Mitigation target (2050)**	
		Project Drawdown	**IMAGE run**
Health and education	Proxy	Increased healthcare, schooling & family planning resources	SSP1 population assumptions

3.8 Excluded from implementation: land use, land sinks & agriculture

Mitigation measures that specifically addressed agricultural practices and/or (coastal) land use, were excluded from this analysis. These include the following sectors (as determined by Project Drawdown): *coastal and ocean sinks*, *engineered sinks*, *food, agriculture & land use* and *land sinks* (Project Drawdown, 2020f), and were excluded due to a limited time frame of the research, as well as constraints within the IMAGE model for this category.

3.9 Calculating Project Drawdown's mitigation scenarios

3.9.1 Determining the reduction potentials in 2050

The modelling outputs of the IMAGE mitigation scenarios were compared with Project Drawdown's emission reduction potentials of *Scenario 1* and *Scenario 2*. Project Drawdown presents cumulative reduction potentials per measure (over 2020 - 2050). For our research, this was translated to sectoral net emission reductions in 2050. For this, emission reduction potentials of individual measures were summed up for each sector, providing the sectoral cumulative reduction potential according to Project Drawdown. Subsequently, the cumulative reduction potential for each sector was translated to an average annual reduction potential. Here, the number of years equals 30 (2020 - 2050). Then, assuming a linear reduction pathway, the average annual reduction potential is multiplied by 2. This leads to the net reduction potential in 2050:

$$Net\ reduction\ potential\ (GtCO_2\text{-}equivalent) = \frac{Cumulative\ reduction\ potential}{Number\ of\ years} \times 2$$

3.9.2 Determining the emission levels in 2050

With the net reduction potentials from Project Drawdown, the anticipated emission levels in 2050 could be calculated (as these were not provided). Project Drawdown states that the emission scenario of the AMPERE project is used as baseline, with no further specification (Frischmann et al., 2020). Therefore, the average across publicly available models of the AMPERE Project is used for the baseline (WP2+3) (AMPERE Database, 2014). The net reduction potentials (2050) of Project Drawdown were subtracted from this averaged AMPERE baseline, providing the global and sectoral emission levels ($GtCO_2$-equivalent) for the Project Drawdown scenarios in 2050.

3.9.3 Linear interpolation towards 2050

As Project Drawdown did not present emission pathways for the entire study period of 30 years, linear interpolation has been applied towards the net emission levels in 2050. This resulted in global and sectoral "Drawdown scenarios" over 2020 - 2050. The IMAGE and Drawdown scenarios are then assessed on global and sectoral scales, differing from Project Drawdown who assessed impacts of individual measures.

3.9.4 AMPERE and SSP2 baselines and 2°C scenarios

The AMPERE and the SSP2 baselines were also included in the data analysis. For the AMPERE baseline, generally the average across models is assumed (AMPERE Database, 2014). However, if this baseline did not yield realistic results for the Project Drawdown mitigation scenarios, another projection of one of the models was considered (indicated in Chapter 4). Additionally, the AMPERE 2°C scenario as well as the SSP2 2°C scenario were incorporated in the analysis, mainly for illustrative reasons. The research method eventually lead to the following scenarios for the data analysis:

- IMAGE *Scenario 1* and *Scenario 2*;
- Drawdown *Scenario 1* and *Scenario 2*;
- Baselines (AMPERE and SSP2);
- 2°C scenarios (AMPERE and SSP2).

4 Results

In Chapter 4, the integrated assessment results of IMAGE are presented after implementing Project Drawdown's mitigation measures. First, the global IMAGE results are given in CO_2-equivalent, and compared to the global reduction potentials of Project Drawdown. Subsequently, the sector results are presented and compared as well.

4.1 Global GHG reduction potentials

According to Project Drawdown, the global net emission reduction potentials of the mitigation measures included in this research, is 32 - 55.6 $GtCO_2$-equivalent in 2050 for *Scenario 1* and *Scenario 2* respectively. This excludes the land use and agricultural measures of Project Drawdown, as well as the small number of measures that were not available yet in IMAGE. A heatmap visualising the replicability of measures in IMAGE is presented in Appendix 7.2. For the global results, Kyoto gas emissions are considered (CO_2-equivalent). The AMPERE baseline and AMPERE 2°C scenario were based on the averaged projection of available models in the AMPERE Database (excluding DNE21 and GCAM) (AMPERE Database, 2014).

Implementation of *Scenario 1* and *Scenario 2* in IMAGE resulted in global GHG emission levels of 53.1 - 49.5 $GtCO_2$-equivalent in 2050 (figure 4.1). According to Project Drawdown, emission levels reached ± 59 - 35 $GtCO_2$-equivalent in that year (figure 4.1). The relative emission reductions for *Scenario 1* and *2* for Project Drawdown were 35 - 61% compared to the AMPERE baseline, and for IMAGE this was 29 - 34% compared to the SSP2 baseline.

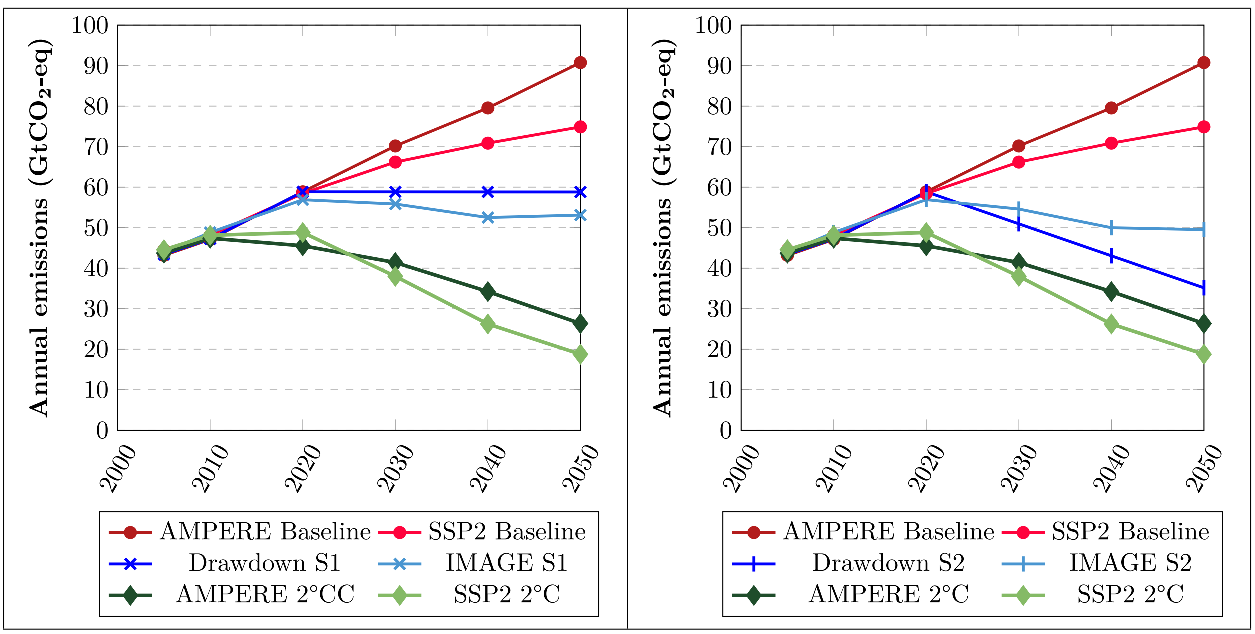

Figure 4.1: Global annual emissions of Kyoto gases ($GtCO_2$-equivalent), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios. The emissions cover the Kyoto gases - carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and F-gases (HFC, PFC & SF6).

Hence, IMAGE found a lower emission level than Project Drawdown for *Scenario 1* in 2050 (-5.7 $GtCO_2$-equivalent), but a higher emission level for *Scenario 2* (+14.4 $GtCO_2$-equivalent). Generally, lower emission levels were anticipated for the IMAGE projections compared to Project Drawdown, as the IMAGE scenarios were based on the SSP2 baseline. The SSP2 baseline is more recent, and generally, more optimistic than the AMPERE baseline in regard to emission levels (figure 4.1). Importantly, there is a large emissions gap between IMAGE and Project Drawdown results in *Scenario 2*. Underlying differences were analysed by means of the sectoral emission reductions. Of the sectors modelled in IMAGE, the largest impact on global GHG emission reductions resides in the *electricity* sector.

4.2 Electricity sector

In Project Drawdown, the net emission reduction potential of the electricity measures is 10.9 - 26.4 $GtCO_2$-equivalent in 2050 (Appendix 7.2). Implementation of *Scenario 1* and *Scenario 2* in IMAGE, projected emission levels of 7.7 - 7.1 $GtCO_2$-equivalent in 2050. According to the reduction potential of Project Drawdown, emission levels reached ± 16 - 0.8 $GtCO_2$-equivalent in that year.

Hence, IMAGE found lower emissions than Project Drawdown for *Scenario 1* in 2050 (-8.6 $GtCO_2$-equivalent), but higher emissions for *Scenario 2* (+6.3 $GtCO_2$-equivalent). The relative emission reductions for *Scenario 1* and *Scenario 2* were 40 - 97% for Project Drawdown compared to the AMPERE baseline, and 70 - 72% for IMAGE compared to the SSP2 baseline. The AMPERE baseline and SSP2 baseline found similar emission levels in 2050 (figure 4.2). The Project Drawdown results in *Scenario 2* were equal to emissions in the AMPERE 2°C scenario in 2050.

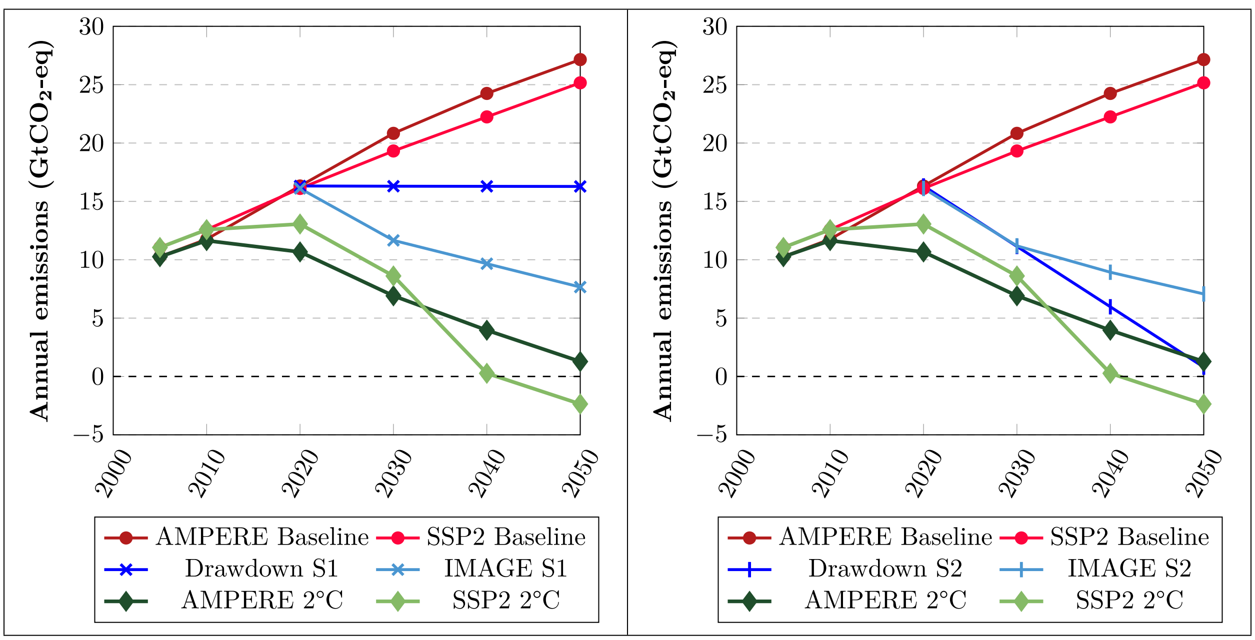

Figure 4.2: Annual emissions in the electricity sector ($GtCO_2$-equivalent, including CO_2), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

By implementing the mitigation strategy of Project Drawdown in IMAGE overall (including the measure *health & education*), a reduced demand for electricity was observed. Where (gross) demand for electricity in 2050 reached 183 Exajoule (EJ) in the SSP2 baseline, this declined with 16 - 18% in *Scenario 1* and *Scenario 2* respectively (figure 4.3).

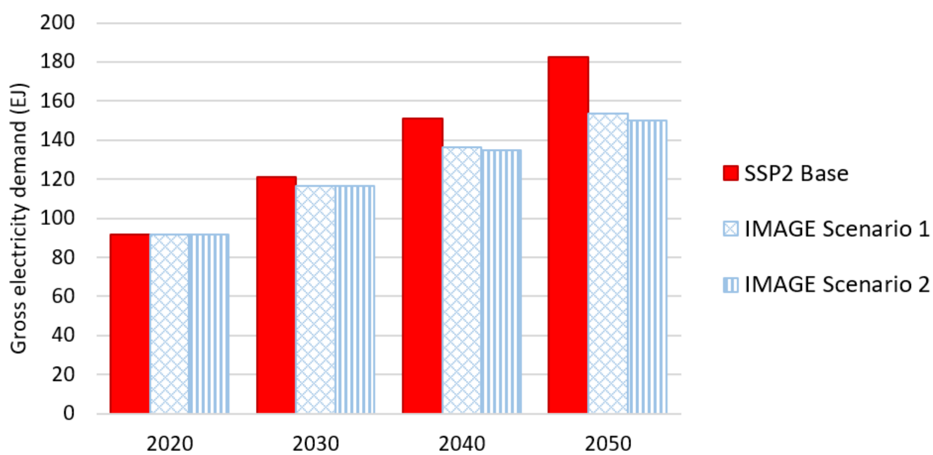

Figure 4.3: Changes in gross electricity demand (Exajoule) during the study period (2020 - 2050) for the SSP2 baseline and the IMAGE mitigation scenarios.

Furthermore, most measures in the mitigation strategy of the *electricity* sector addressed the global electricity generation mix in 2050 (table 1, Chapter 3). Project Drawdown accounts the largest emission reduction impacts to the increased supply of electricity through the renewables *onshore wind turbines*, *utility-scale photovoltaics* and *distributed solar photovoltaics*. These technologies together should provide $\pm 53 - 66\%$ of the global electricity in 2050, and are responsible for a net reduction of 7.8 - 22 $GtCO_2$-equivalent in 2050 for *Scenario 1* and *2* respectively. In TIMER, a maximum target of $\pm 45 - 50\%$ was reached for these three technologies, which does not equal Project Drawdown's targets. Yet, the electricity generation mix becomes substantially different from the SSP2 baseline (figure 4.4), and emission reductions found in *Scenario 1* were greater in IMAGE than in Project Drawdown.

Other changes in the electricity generation mix, relative to the SSP2 baseline, were caused by increases in *offshore wind*, *concentrated solar power (CSP)* and *nuclear power*, which together provide circa 12 - 13% of global electricity in the mitigation scenarios in 2050 (figure 4.4). Simultaneously, *natural gas*, *conventional oil* and *conventional coal* were reduced in both *Scenario 1* and *2*. In the SSP2 baseline, these fossil fuels make up 33% of electricity supply in 2050, but only contribute 12 - 13% in *Scenario 1* and *2* respectively. For *biomass*, Project Drawdown defined shares of ca. 1% in *Scenario 1*, and <1% in *Scenario 2*. Due to these low shares, *biomass* followed the SSP2 baseline assumptions, which were affected by the changes in the other electricity supply technologies. In the SSP2 baseline, *biomass* contributed 2% in 2050, but the contributions became negligible in the mitigation scenarios in 2050 (figure 4.4).

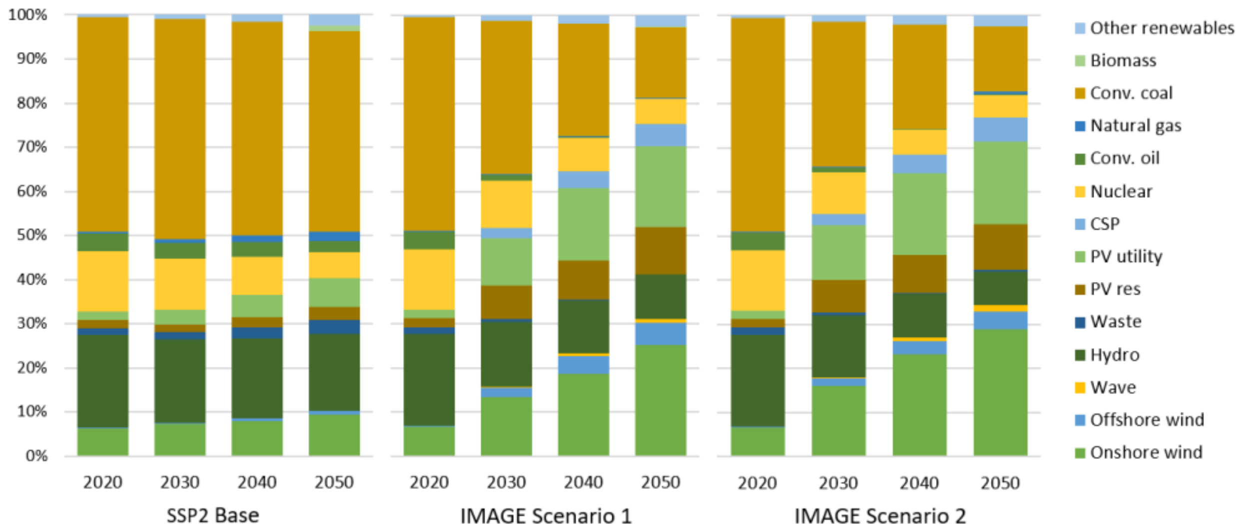

Figure 4.4: Changes in the electricity generation mix during the study period (2020 - 2050) for the SSP2 baseline and the IMAGE mitigation scenarios.

4.3 Transport sector

In Project Drawdown, the net emission reduction potential of the implemented transport measures is 3.8 - 6.2 $GtCO_2$-equivalent in 2050 (Appendix 7.2). Implementation of transport measures for *Scenario 1* and *Scenario 2* in IMAGE lead to emission levels of 9.9 - 8.4 $GtCO_2$-equivalent in 2050 (figure 4.5). Based on the reduction potential of Project Drawdown, emission levels reached ± 9 - 6.6 $GtCO_2$-equivalent in 2050 (figure 4.5).

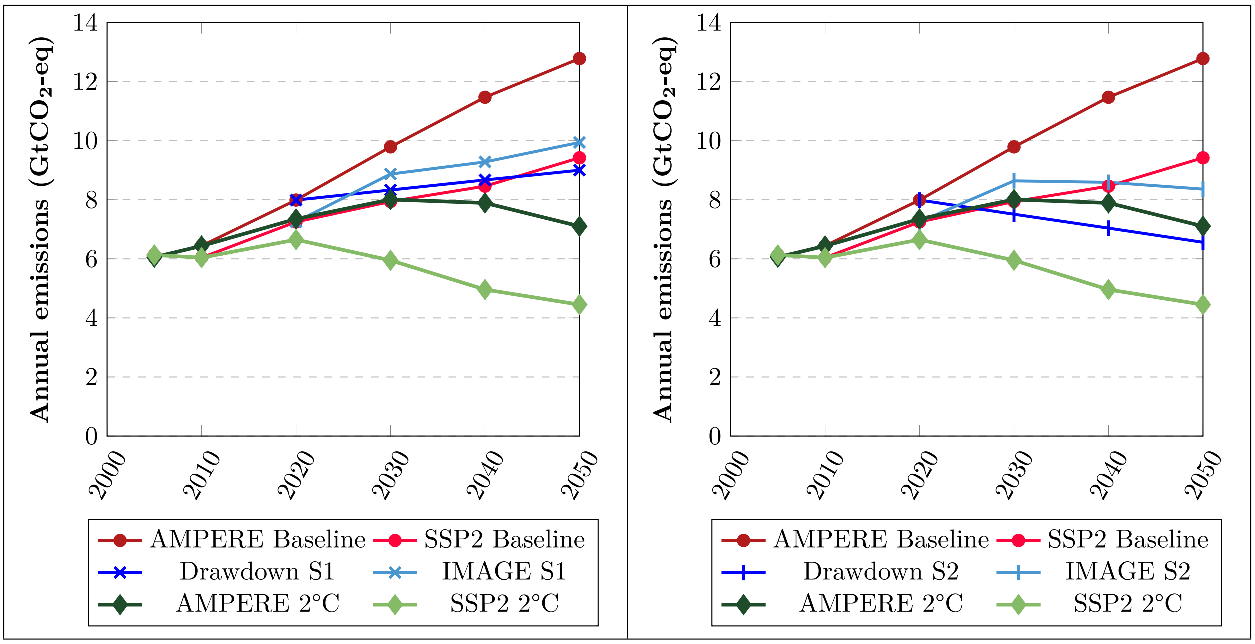

Figure 4.5: Annual emissions in the transport sector ($GtCO_2$-equivalent, including CO_2 and CH_4), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

Hence, IMAGE found higher emissions than Project Drawdown for *Scenario 1* (+0.9 $GtCO_2$-equivalent) and also for *Scenario 2* (+1.8 $GtCO_2$-equivalent). In 2050, relative emission reductions for *Scenario 1* and *Scenario 2* were 30 - 49% for Project Drawdown compared to the AMPERE baseline, and -6 - 11% for IMAGE compared to the SSP2 baseline.

The 2050 emission level of the SSP2 baseline in *Scenario 1* is similar to the IMAGE and Project Drawdown scenarios. Here, all three scenarios lie between 9 - 10 $GtCO_2$-equivalent emissions (figure 4.5). However, the SSP2 baseline reached lower emissions than IMAGE *Scenario 1* in 2050. In *Scenario 2*, emissions declined after 2030, whereafter the IMAGE projection becomes more optimistic than the SSP2 baseline. It is likely that this trend was caused by a delay in the availability of the blended wing body air crafts, which were applied to increase vehicle efficiency. Moreover, in *Scenario 2*, Project Drawdown's emission level was lower than the AMPERE 2°C scenario.

The transport sector is divided in passenger and freight transport (table 2, Chapter 3). The passenger measures addressed either a change in the usage of modes, or a change in efficiency in certain vehicle types within a mode. The greatest impacts on emission reductions according to Project Drawdown, when considering the usage of modes, result from *carpooling* and *public transit*. After the implementation of measures in IMAGE, bus use reduced by 11 - 30%, car use reduced by 11 - 28% and air travel by 4 - 24%, relative to the SSP2 baseline (figure 4.6). Walking increased with roughly 20 - 100% in 2050, and biking increased with ca. 68 - 500%. Use of high-speed trains (HST) and conventional trains slightly increased.

The reduction in car use corresponds to the concept of *carpooling*, and is influenced by increased adoption of other modes (i.e., biking). The share of buses (i.e., public transit) generally declined compared to the SSP2 baseline. This potentially relates to the assumption of Project Drawdown, where public transit adoption may become relatively low in Asia and Africa (Project Drawdown, 2020r). Despite this, it contributes greatly to the reduction potential, according to *Project Drawdown*.

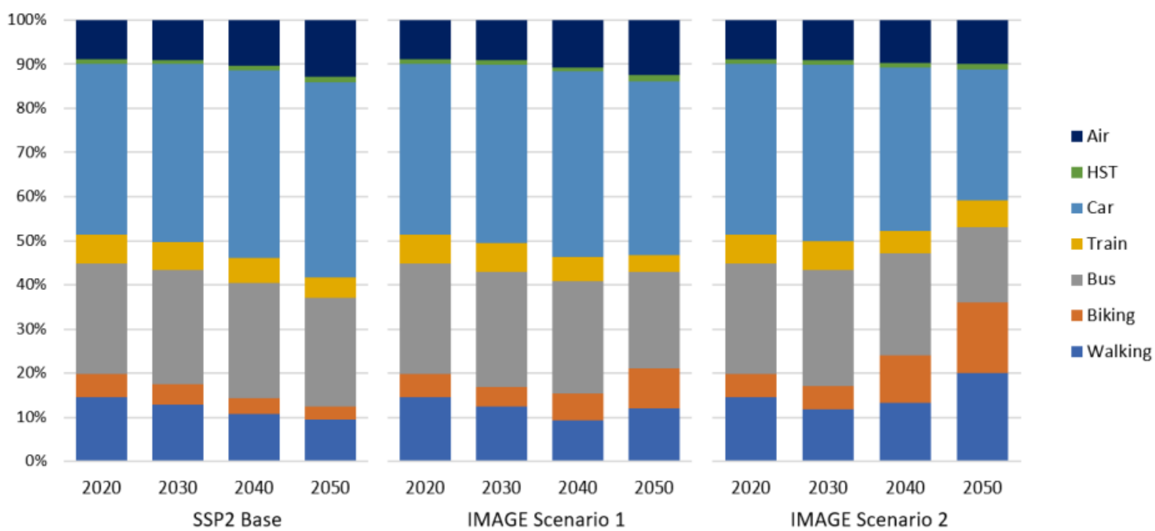

Figure 4.6: Changes in the modal split for passenger travel during the study period (2020 - 2050) for the SSP2 baseline, and the IMAGE mitigation scenarios.

The efficiency gains of vehicle types (coupled with reduced use of certain passenger modes as described above), were analysed through the energy use per mode (excluding walking and biking). In Project Drawdown, the largest emission reductions through vehicle efficiency result from the adoption of *electric cars* and *hybrid cars*. In IMAGE, the secondary energy use of cars in the SSP2 baseline was approximately 43 EJ in 2050. In mitigation *Scenario 1* and *Scenario 2*, this is reduced by 9 - 45% in 2050. Furthermore, a change in energy use is mainly visible for air travel, which is 27.3 in the SSP2 baseline in 2050, and declines with 12 - 36% in *Scenario 1* and *2* respectively. Reduced energy use for buses is caused by lower adoption of this mode, while the increase in energy use for trains slightly increases due to higher adoption of the mode. Overall, energy use in passenger transport in 2050 was reduced by 11 - 39% in *Scenario 1* and *Scenario 2*, relative to the SSP2 baseline.

The mitigation measures for freight transport only addressed the adoption of efficient vehicle types, and consist of *electric trains*, *efficient ocean shipping* and *efficient trucks*. These measures did not have the greatest impact on emission reductions when considering the complete *transport* sector. Still, the latter two measures should result in higher emission reductions than *electric trains*. In IMAGE, energy use for trucks (medium + heavy) was 50 EJ in the SSP2 baseline in 2050, and declined with 6% in *Scenario 1* and 14% in *Scenario 2*. International shipping accounted for 9.4 EJ in the SSP2 baseline, and declined with 15% in *Scenario 1* and 19% in *Scenario 2* in the same year. Finally, freight trains accounted for 6.2 EJ in the SSP2 baseline, which declined with 23% in *Scenario 1* and 10% in *Scenario 2*. Here, the greater decline in energy use in *Scenario 1* compared to *Scenario 2*, corresponds to the larger amount of *electric trains* in *Scenario 1*.

In contrast to the lower energy use in both passenger and freight transport in *Scenario 1* (figure 4.7, 4.8), the emission level of IMAGE *Scenario 1* is higher in 2050 compared to the SSP2 baseline (figure 4.5).

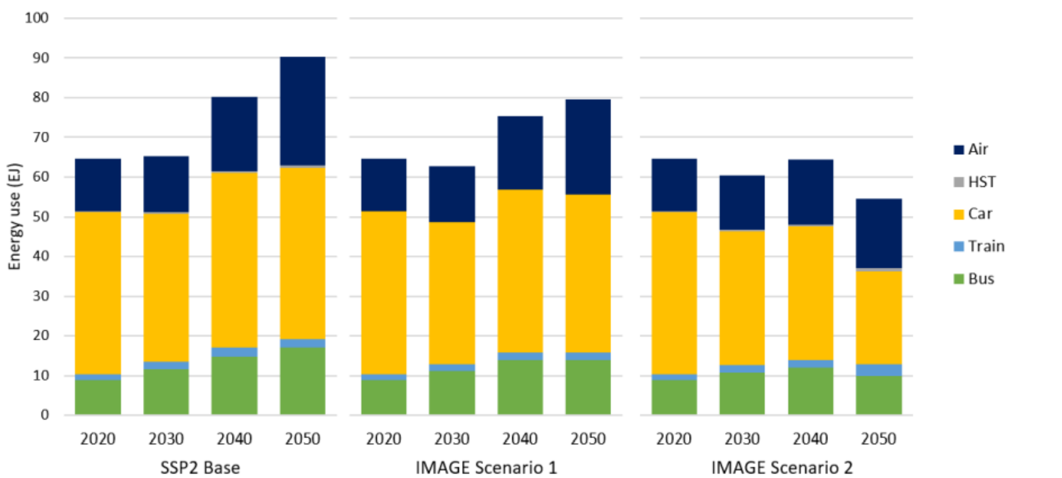

Figure 4.7: Changes in the energy use (EJ) for passenger travel during the study period (2020 - 2050) for the SSP2 baseline, and the IMAGE mitigation scenarios.

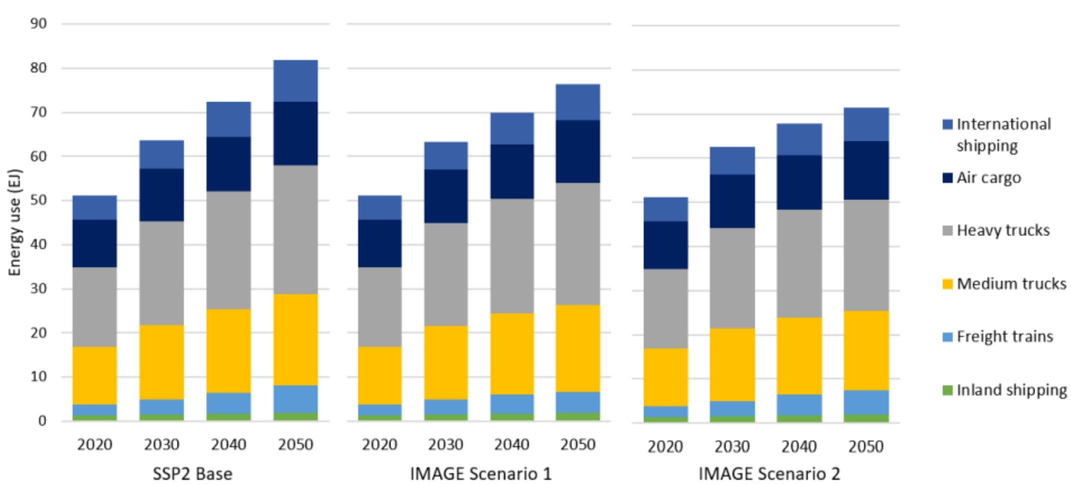

Figure 4.8: Changes in the energy use (EJ) for freight transport during the study period (2020 - 2050) for the SSP2 baseline, and the IMAGE mitigation scenarios.

4.4 Residential sector

According to Project Drawdown, the emission reduction potential of the residential measures were 4.4 - 6.1 $GtCO_2$-equivalent in 2050. Implementations in IMAGE for *Scenario 1* and *Scenario 2* were projected to result in emission levels of 3.2 - 3 $GtCO_2$-equivalent in 2050. When using the average across models of the AMPERE baseline for the reduction potential of Project Drawdown, the latter finds emission levels of ± 1.45 - -0.3 $GtCO_2$-equivalent (Appendix 7.3, figure 7.1). Indicating that in this case, Project Drawdown found a reduction that is 2-3 as high as found by IMAGE in 2050, leading to negative emissions in *Scenario 2*, it is assumed that Project Drawdown applied a higher baseline projection.

Therefore, for the residential sector, the highest baseline projection of the AMPERE baseline is used instead (GCAM). Relative to this baseline, Project Drawdown reached emission levels of ± 4 - 2.3 $GtCO_2$-equivalent in *Scenario 1* and *Scenario 2* respectively (figure 4.9). Proceeding with the GCAM baseline, IMAGE found lower emission levels than Project Drawdown for *Scenario 1* (-0.8 $GtCO_2$-equivalent), but higher emissions for *Scenario 2* (+0.7 $GtCO_2$-equivalent). Emission reductions in 2050 for *Scenario 1* were 52 - 73% for Project Drawdown (relative to the GCAM AMPERE baseline), and 29 - 35% for IMAGE (relative to the SSP2 baseline). In both *Scenario 1* and *2*, IMAGE reached emission levels equal to the AMPERE and SSP2 2°C scenarios.

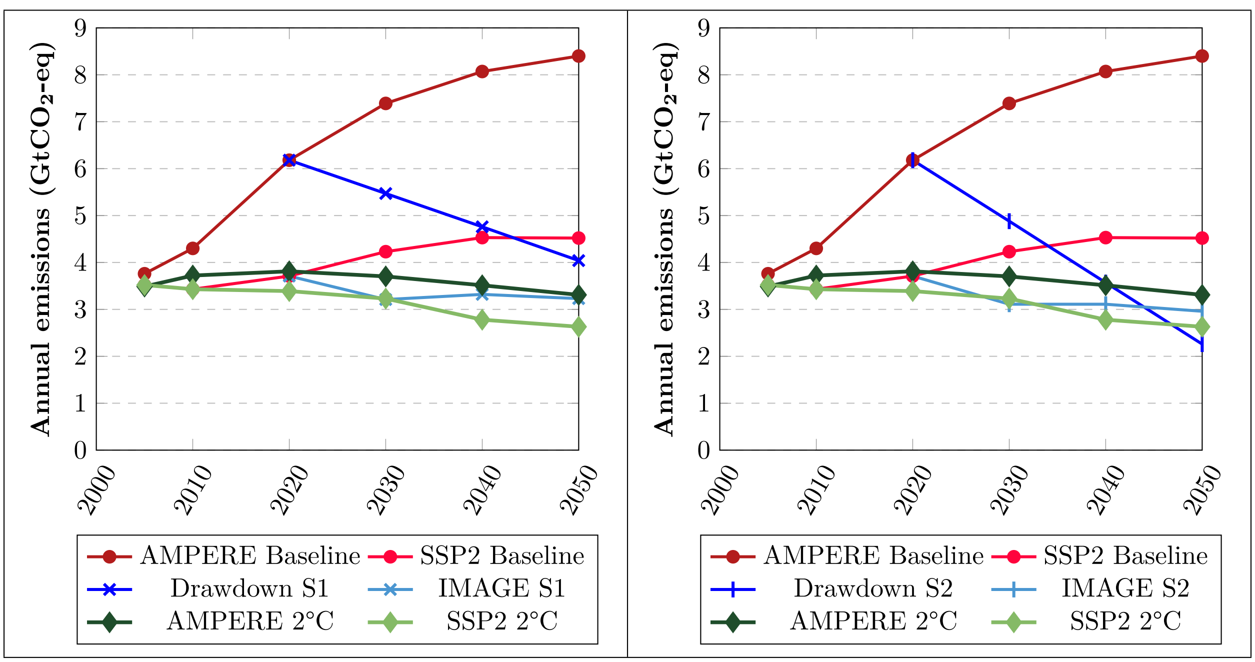

Figure 4.9: Annual emissions in the residential sector ($GtCO_2$-equivalent, including CO_2 and CH_4), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

Mitigation measures that addressed *improved clean cookstoves* and *biogas for cooking* were accounted for in the non-CO_2 sector, due to the contributions of CH_4 emissions. Thus, the residential emissions pathway of Project Drawdown in figure 4.9 does not include emissions from cooking, whilst the CO_2 emissions from cooking are included in the IMAGE mitigation scenarios.

In Project Drawdown, the largest impacts on emission reductions in the *residential* sector result from *insulation*, *high performance glass* and *LED lighting* (excluding the cooking measures). These should account for 2.9 – 3.3 $GtCO_2$-equivalent reduction in 2050. *Solar hot water* plays an important role in *Scenario 2* as well. Impacts of these measures in IMAGE were analysed by the energy end use for space heating and cooling, lighting and water heating (figure 4.10). Space heating accounts for 26 EJ in the SSP2 baseline in 2050, and declines with 19% in *Scenario 1* and 31% in *Scenario 2*. In that same year, energy use from space cooling was 9 EJ in the SSP2 baseline, and is reduced with 13% in *Scenario 1* and 22% in *Scenario 2*. Lighting accounts for 4.6 EJ in 2050 in the SSP2 baseline, and declined with ca. 25% in both mitigation scenarios.

In total, residential energy use was reduced by 20 – 28% relative to the SSP2 baseline, which is partly driven by reduced demand (i.e., due to a smaller global population). Energy use for household appliances was not affected by the modelled mitigation strategy; however, it might be affected through *building automation systems (BAS)*, which is a measure included in Project Drawdown, but not included in our research (Appendix 7.2).

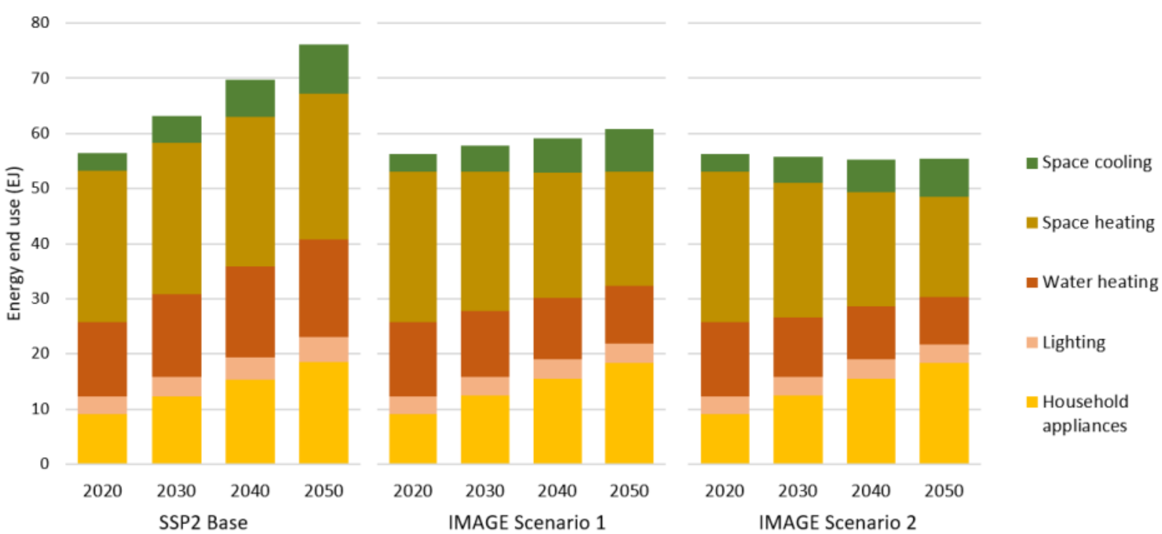

Figure 4.10: Changes in the energy use (EJ) for the residential sector during the study period (2020 - 2050) for the SSP2 baseline, and the IMAGE mitigation scenarios.

4.5 Industry sector

In Project Drawdown, the emission reduction potential of the industry measures was 1 - 1.6 $GtCO_2$-equivalent in 2050. Implementations for *Scenario 1* and *Scenario 2* in IMAGE lead to emission levels of 6.6 - 6.3 $GtCO_2$-equivalent in 2050. With regards to Project Drawdown's reduction potential, Project Drawdown reached ± 14 - 13 $GtCO_2$-equivalent in that year. Hence, IMAGE found lower emissions than Project Drawdown for *Scenario 1* (-7.4 $GtCO_2$-equivalent) and *Scenario 2* (-6.7 $GtCO_2$-equivalent).

Relative emission reductions in 2050 were, for *Scenario 1* and *Scenario 2*, 7 - 12% for Project Drawdown compared to the AMPERE baseline. For IMAGE, these were 29 - 39% compared to the SSP2 baseline. Differences in emission levels of Project Drawdown and IMAGE are influenced by differences in the initial baselines (the SSP2 baseline emissions are already 39% lower than those of the AMPERE baseline).

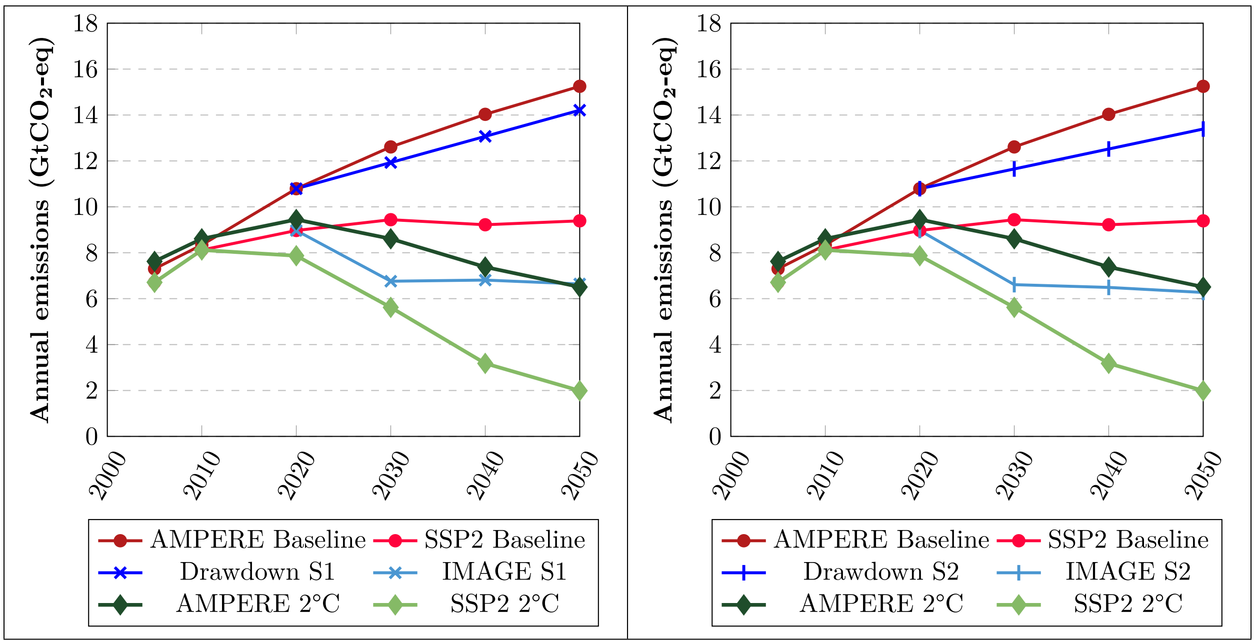

Figure 4.11: Annual emissions in the industry sector ($GtCO_2$-equivalent, including CO_2 and CH_4), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

In Project Drawdown, the greatest emission reductions in the *industry* sector are accounted to *alternative cement*. The mitigation measure for cement addressed lower clinker/cement ratios in 2050, which lead to reduced production rates of cement and clinker (figure 4.12). In the SSP2 baseline, production quantities in 2050 reached 3,200 million tonnes (Mt). This is diminished to 2,450 Mt in *Scenario 1* (-23%) and 1,847 Mt in *Scenario 2* (-42%) in that year.

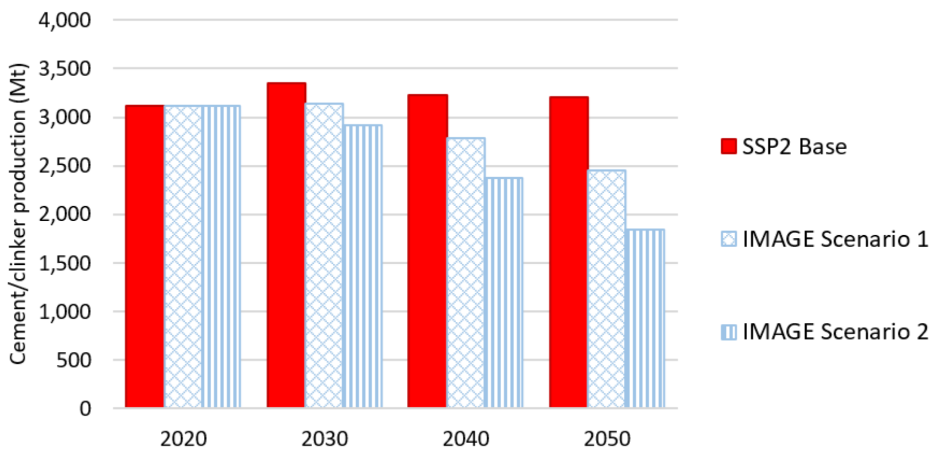

Figure 4.12: Cement/clinker production in million tonnes (Mt) for the SSP2 baseline and the IMAGE mitigation scenarios.

4.6 Non-CO2 sector

According to Project Drawdown, the emission reduction potentials of the measures addressing CH_4 emissions was 3.3 - 6 $GtCO_2$-equivalent in 2050. This also includes emission reduction potentials of the cooking measures (table 5, Chapter 3). Implementation of the CH_4 measures in IMAGE for *Scenario 1* and *Scenario 2*, lead to emission levels of 5 $GtCO_2$-equivalent in 2050 (figure 4.14). IMAGE and Project Drawdown found an equal emission level in *Scenario 1*, but Project Drawdown found a lower emission level in *Scenario 2* (-1.7 $GtCO_2$-equivalent).

Relative emission reductions in 2050 for Project Drawdown's *Scenario 1* and *Scenario 2*, were 46 - 64% compared to the AMPERE baseline. For IMAGE, relative emission reductions were 28% for both scenarios, compared to the SSP2 baseline. The reason why the reduction potential of IMAGE stayed the same, could be explained due to higher CH_4 emissions from the non-CO_2 sector, but lower CH_4 emissions from the other sectors. Here, higher CH_4 emissions from the non-CO_2 sector are caused by lower adoption rates of *methane digesters* and *landfill methane capture* in *Scenario 2* (table 5, Chapter 3).

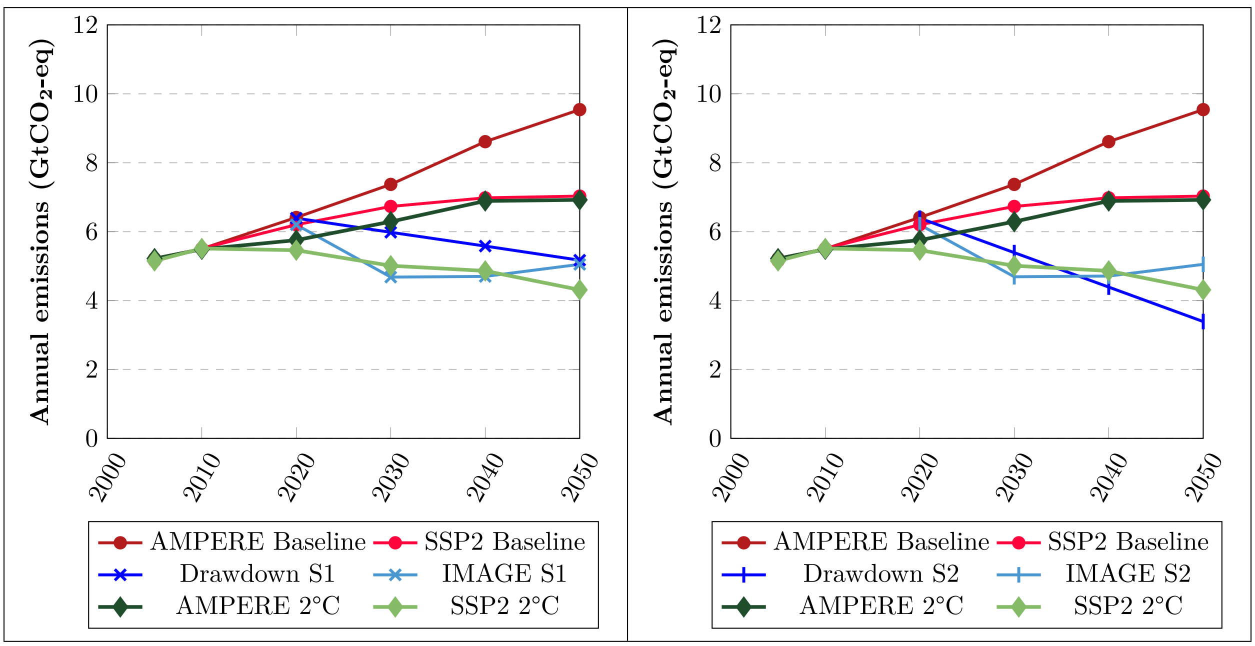

Figure 4.13: Annual emissions in the non-CO_2 sector ($GtCO_2$-equivalent, including CH_4) resulting from AFOLU and waste, projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

CH_4 emissions in IMAGE were strongly reduced until 2030, but increased again slightly towards 2050. This is presumably due to the *improved clean cookstoves* measure, which was supposed to meet its targets already in 2030 (table 5, Chapter 3). Therefore, the premium factor to promote clean cooking was implemented until 2030. According to Project Drawdown, this *improved clean cookstoves* did account for the greatest part of the emission reductions in this sector. It is, however, not clear if Project Drawdown's emission pathway follows the same trend as found in IMAGE, as linear interpolation was applied towards emission levels in 2050.

Moreover, other non-CO_2 emissions that were addressed in this sector resulted from F-gases. In Project Drawdown, the *alternative refrigerant* measure accounted for a net emission reduction of 2.9 - 3.4 $GtCO_2$-equivalent in 2050. Implementation of this measure in IMAGE for *Scenario 1* and *Scenario 2* lead to emission levels of 1.3 - 1 $GtCO_2$-equivalent in 2050. Regarding the reduction potentials of Project Drawdown, the latter found emission levels of ± -0.7 - -1.2 $GtCO_2$-equivalent when using the average across models for the AMPERE Baseline (AMPERE Database, 2014) (Appendix 7.4, figure 7.2). However, this would indicate that Project Drawdown finds a reduction potential that is roughly twice as high as that of IMAGE, reaching negative emissions for total F-gases only through one measure addressing HFC refrigerants. Therefore, it is assumed that Project Drawdown applied a higher baseline projection.

Thus for the F-gases, the highest baseline projection of the AMPERE baseline is used instead (AMPERE IMAGE). Relative to this baseline, Project Drawdown found similar emission levels to IMAGE (± 1.4 - 1 $GtCO_2$-equivalent) (figure 4.13). The relative emission reductions in 2050 were, for *Scenario 1* and *Scenario 2* in Project Drawdown, 67 - 78 % compared to the IMAGE AMPERE baseline, and 59 - 69% for IMAGE compared to the SSP2 baseline.

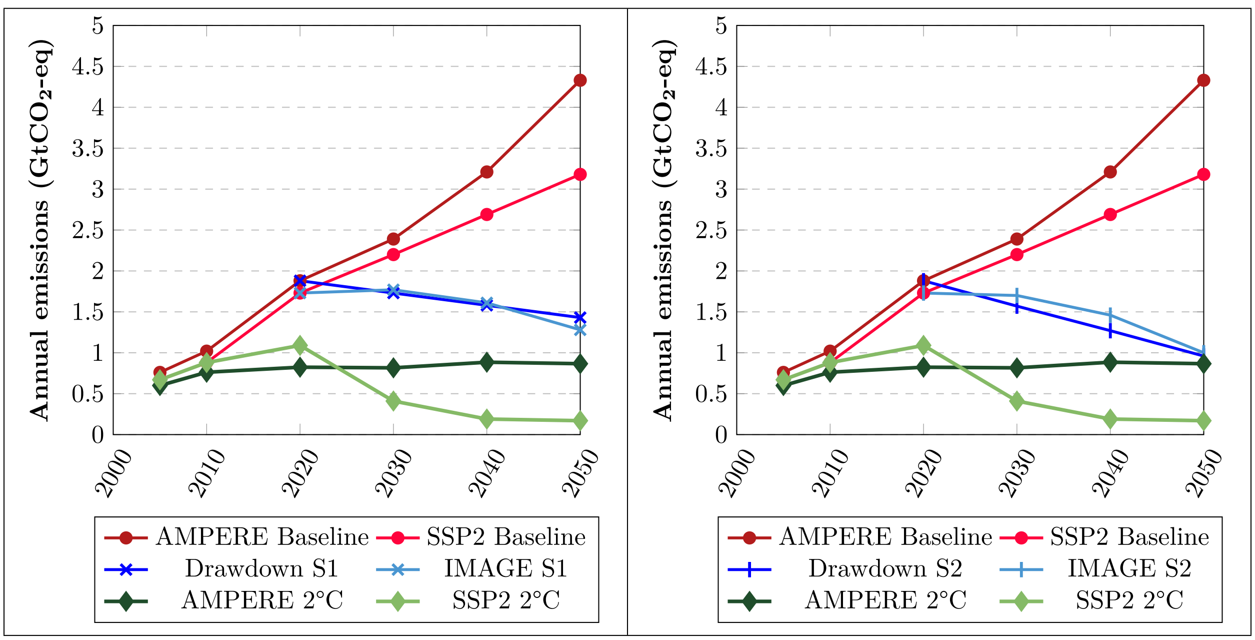

Figure 4.14: Annual emissions in the non-CO_2 sector ($GtCO_2$-equivalent) resulting from F-gases, projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

In *Scenario 1*, the two mitigation scenarios and the AMPERE 2°C scenario lie between emission levels 0.9 - 1.5 $GtCO_2$-equivalent in 2050. In *Scenario 2*, this similarity is stronger, and these three scenarios reached an emission level of 0.9 - 1 $GtCO_2$-equivalent.

5 Discussion

In Chapter 5, the global and sectoral findings are discussed. Thereafter, the limitations of this research are presented, but also the added value of the research is provided.

5.1 Global findings

In this research, the emission reduction potentials found by Project Drawdown for individual mitigation measures, were assessed in integrated assessment model IMAGE on a global and sectoral scale. Integrated assessment allowed dynamics to occur, such as interactions between implementations, inertias in the climate system as well as regional variation. Therefore, it was expected that new insights would emerge from this approach, as different models include varying assumptions (Blok et al., 2020). Results did demonstrate some differences as well as similarities between Project Drawdown and IMAGE.

Global findings of emission levels for both Project Drawdown and IMAGE were relatively similar. This was especially the case for *Scenario 1*, where Project Drawdown found 59 $GtCO_2$-equivalent in 2050, and IMAGE found 53 $GtCO_2$-equivalent. Lower emission levels were anticipated for the IMAGE scenarios as the IMAGE runs were based on the SSP2 baseline, which projects lower emissions than the AMPERE baseline. In *Scenario 2*, the mitigation scenarios "switched places", and larger differences were found between the two approaches. Project Drawdown found an emission level of 35 $GtCO_2$-equivalent in 2050, whereas IMAGE found 49.5 $GtCO_2$-equivalent. Thus, the results of *Scenario 2* showed larger differences than the results of *Scenario 1*. Global results were then analysed through the sectoral findings.

5.2 Sectoral findings

The sectors *electricity*, *transport*, *residential*, *industry* and *non-CO_2* were analysed to assess integration between measures. Project Drawdown's measures that addressed "land & agricultural" practices, were excluded from analysis. Of all sectors, IMAGE found the greatest reduction potentials within the *electricity* sector, similar to findings by Roelfsema et al. (2018).

For the electricity sector, IMAGE found a reduction potential roughly twice as high as Project Drawdown for *Scenario 1*, whilst the renewable electricity shares in TIMER did not all meet the Project Drawdown targets. This might indicate that Project Drawdown used conservative assumptions in regard to the reduction potential. However, this suggestion would be contradicted by *Scenario 2*, where Project Drawdown found higher emission reductions than IMAGE. In both IMAGE scenarios, not all regions in TIMER could reach the electricity production targets that were implemented. To overcome this barrier, additional changes in the IMAGE model are needed. The question is whether these targets are realistic if such adaptations are required.

For the transport sector, IMAGE found emission levels that were relatively similar to Project Drawdown, but the latter was slightly more optimistic. If Project Drawdown used a higher AMPERE baseline projection, this would minimise the differences found between the Project Drawdown and IMAGE. Moreover, the SSP2 baseline reached lower emission levels than *Scenario 1* in IMAGE - indicating that SSP2 accounts for more efficient transport than suggested by Project Drawdown. This could be the case, as the SSP2 baseline is a more recent projection (2017) than the AMPERE baseline (2014). However, passenger and freight transport did show a reduction in energy use in *Scenario 1* compared to the SSP2 baseline. Potentially, higher emissions are due to changes in energy carriers that are not addressed in Project Drawdown. This aspect could be researched further.

In the residential sector, when the average baseline across models was used for the AMPERE baseline, negative emissions were found for Project Drawdown's *Scenario 2*. This was considered unrealistic, and lead to the adoption of the highest projection of the AMPERE baseline (AMPERE GCAM). Here, emission levels of Project Drawdown were similar to those found in IMAGE. Project Drawdown found higher emission level in *Scenario 1*, whilst IMAGE found a higher emission level in *Scenario 2*. The IMAGE scenarios also lead to similar emission levels as the 2°C scenarios. Regarding the use of assumptions for the AMPERE baseline, this sector showed the importance of clarity on the methodology used for Project Drawdown.

In the industry sector, the AMPERE and SSP2 baselines are dissimilar. This resulted in large differences in the emission levels of Project Drawdown and IMAGE. Taking into account the relative emission reductions, IMAGE was more optimistic than Project Drawdown overall. This difference might be due to the interpretation that is given to the general *recycling* measure. In TIMER, recycling was implemented for steel and plastics, for which the general recycling rate of Project Drawdown could not be used. In this case, Project Drawdown could provide more disaggregated information.

In the non-CO_2 sector, emissions were divided over CH_4 emissions resulting from AFOLU and waste, and F-gases. For CH_4 emissions, IMAGE finds the same emission level in *Scenario 1* as in *Scenario 2*. That is because CH_4 emissions due to AFOLU and waste increase in *Scenario 2*, due to lower adoption of *methane digesters* and *landfill methane capture*. Simultaneously, CH_4 emissions from the other sectors were reduced. Moreover, emissions in the IMAGE scenarios were greatly reduced until 2030, but increased again thereafter. This was due to the *improved clean cookstoves* measure, which had mitigation targets for 2030. It is unclear whether the increase in emissions after 2030 were also found in Project Drawdown, as linear interpolation is used towards 2050 in our research. For the F-gases, when using the average across models for the AMPERE baseline, Project Drawdown would find negative emission levels which, could not be reached by a single HFC refrigerant measure. When the highest baseline projection was applied (AMPERE IMAGE), Project Drawdown and IMAGE found equal emission levels. Again, the F-gases stressed the importance of the replicability of the methodology used in Project Drawdown.

5.3 Limitations of the research

Our research was limited to modelling 47 measures in IMAGE, of the ca. 80 measures that were applied in Project Drawdown (Appendix 7.2). The land use and agriculture measures were initially not included, as these addressed the enhancement of carbon sequestration through relatively modern and/or specific concepts, which are not all included (yet) in IMAGE. Examples are: *tree intercropping*, *managed grazing*, *bamboo*, and *women smallholders*. Here lies a potential to expand modelling options in IMAGE for this category. Concepts such as agroforestry, silvopasture and restoration of degraded lands are being worked on in the Global Land Outlook project (GLO2), but were not yet available at the time of this research.

Moreover, our research was not always able to apply the exact methodology that was used in Project Drawdown. Project Drawdown provides much descriptive information on its website, but data that is used is not always publicly available. Moreover, some information was not given. An important example is the lack of clarity surrounding the baseline scenario used in Project Drawdown. It is stated that Drawdown "used the work of AMPERE" - but additional information is not provided (Frischmann et al., 2020). In our research, the baseline was assumed to be the average emission level across all models that are part of the AMPERE project (AMPERE Database, 2014). However, this resulted in very high emission reductions for the Project Drawdown scenarios in the *residential* sector, as well as the *F-gases*. This often lead to negative emissions, whereafter the highest emission projection within the AMPERE baseline was applied. This yielded better results. Thus, it is advised that Drawdown is more transparent about the used methodology, as it is not clear what emission levels are actually reached if only a reduction potential relative to a unspecified baseline is provided.

Reduction potentials that were found in this research, do also greatly depend on management and governance aspects (Avelino et al., 2016; Roelfsema et al., 2018). Even though the objective of Project Drawdown is to analyse what the reduction potential *could* be by using existing knowledge - it remains important for corporations (and individuals) to have an incentive to adopt mitigation measures (i.e. "*how* can the ambitious target of adopting 80-85% efficient air crafts in 2050 be reached, without applying a carbon tax?"). Including socio-economic or governance components in the Project Drawdown research is advised, as this can make it more realistic in its approach to reach the climate targets of the Paris Agreement.

Lastly, it is carefully considered that uncertainties are inherent to climate modelling, due to complex relations as well as assumptions on future scenario drivers, the level of aggregation, etc. (Stehfest et al., 2014). However, IMAGE has been developed over many years and is improved continuously. In order to reduce uncertainties about the approach, our research aimed to be as transparent as possible about its methodology.

5.4 Added value of the research

In sum, our research has provided insights into the approach used in Project Drawdown, as it is supplemented with data on GHG emissions resulting from different sectors. Also, potential areas for improvement for Project Drawdown and IMAGE were identified. This contributed to upholding the transparency, and thus integrity, of existing research. In addition, our research generally provided comprehensive information on reduction potentials on global and sectoral scales, taking into account different types of GHGs. The research presented avenues for further research - potentially by Drawdown, or other interested parties.

6 Conclusion

In Chapter 6, the sub-questions and main research question, which were presented in the Introduction, are answered using the implications of the Discussion.

How can Project Drawdown's mitigation strategy be adequately implemented in IMAGE?

The implementation of Project Drawdown's mitigation strategy in IMAGE posed some challenges. This was due to (i) the lack of transparency within Project Drawdown, resulting in the use of assumptions throughout our modelling approach, and (ii) the inability to implement all mitigation measures of Project Drawdown in IMAGE. Most importantly, assumptions were made about the AMPERE baseline scenario, as this was not specified by Drawdown. Also, assumptions were made to retrieve usable data for implementations in the IMAGE model. In the *residential* sector, many proxies had to be applied (Appendix 7.2). The "land & agriculture" sectors of Project Drawdown included the most measures that were not represented by IMAGE, and were therefore excluded from analysis.

What are the sectoral reduction potentials of the measures according to IMAGE?

Relative to the SSP2 baseline, emission reductions were found for the *electricity* sector of 70 - 72%. IMAGE found a greater reduction potential in *Scenario 1* than Project Drawdown, leading to a lower emission level. IMAGE found a lower reduction potential in *Scenario 2*, and a higher emission level compared to Project Drawdown. *Scenario 2* showed a larger emissions gap between IMAGE and Project Drawdown.

Relative to the SSP2 baseline, emission reductions were found for the *transport* sector of -6 - 11%. IMAGE found lower reduction potentials and higher emission levels in *Scenario 1* and *Scenario 2* compared to Project Drawdown. *Scenario 2* showed a larger emissions gap between IMAGE and Project Drawdown.

Emission reductions found for the *residential* sector were 29 - 35% relative to the SSP2 baseline. IMAGE found lower reduction potentials in *Scenario 1* and *Scenario 2* than Project Drawdown, but found similar emission levels. Yet, Project Drawdown's *Scenario 2* found a lower emission level in 2050.

Relative to the SSP2 baseline, emission reductions were found for the *industry* sector of 29 - 39%. IMAGE found higher reduction potentials and lower emission levels in *Scenario 1* and *Scenario 2*. *Scenario 2* showed a smaller emissions gap between IMAGE and Project Drawdown.

Lastly, emission reductions were found for the *non-*CO_2 of 28% for CH_4 emissions relative to the SSP2 baseline, and 59 - 69% for F-gas emissions. For CH_4 emissions, IMAGE and Project Drawdown found an equal emission level in *Scenario 1*, but *Scenario 2* showed a larger emissions gap between IMAGE and Project Drawdown. For F-gases, emission levels were very similar for both IMAGE and Project Drawdown, and in *Scenario 2* they found an equal emission level.

Thus, Project Drawdown found more optimistic reduction potentials in multiple sectors for *Scenario 2* than IMAGE. Differences between Project Drawdown and IMAGE were generally smaller for *Scenario 1*.

What can an integrated assessment modelling approach in IMAGE tell us about Project Drawdown's mitigation strategy and global emission reduction potential?

In conclusion, the findings of the IMAGE model showed that substantial GHG emission reductions could take place with the current knowledge that is included in the mitigation measures of Project Drawdown. IMAGE and Project Drawdown had minor differences in their findings for *Scenario 1*. However, larger differences were found for *Scenario 2*, where IMAGE often did not reach Project Drawdown's emission reductions. In regard to Project Drawdown's mitigation strategy, more transparency is required, as differences in assumptions lead to different findings.

However, a relatively consistent pattern was found in reduction potentials for *Scenario 1* and *Scenario 2*, where *Scenario 2* often found lower emission reductions in IMAGE compared to Project Drawdown. This indicated that differences emerged due to the integration of measures, especially for *Scenario 2*. Differences between Project Drawdown and IMAGE findings were expected to occur, due to the integration of mitigation measures. The mutual implementation of measures in IMAGE showed a lower reduction potential for *Scenario 2* overall.

Utrecht University

PBL Netherlands Environmental Assessment Agency

Acknowledgements

Foremost, I want to thank my supervisors Prof. dr. Detlef van Vuuren and Dr. Andries Hof, who gave me the opportunity to work on this research project at PBL Netherlands Environmental Assessment Agency. Detlef and Andries have supported me throughout the research, and gave advice when I needed it. I learned many things, on an academic as well as personal level.

Furthermore, I want to express my gratitude to the experts at PBL Netherlands Environmental Assessment Agency, who helped me with the sectoral assessments and modelling approaches - Oreane Edelenbosch, Vassilis Daioglou, Harmen-Sytze de Boer & Mathijs Harmsen. A special thanks to David Gernaat for taking the time to explain me modelling structures in IMAGE. Also, I am grateful for advice about the industry sector, provided by Mariësse Sluisveld.

Lastly, I am sincerely grateful for feedback that I have received for writing this thesis. The second reader of this report, Dr. Birka Wicke, provided me with feedback based on my initial research proposal. Also Drs. Mark Roelfsema provided feedback based on the latest versions of this thesis. Rik Paanakker, a fellow MSc student at Utrecht University, made time to peer-review the thesis as well.

Bibliography

AMPERE Database (2014). *About AMPERE*. https://tntcat.iiasa.ac.at/AMPEREDB/dsd?Action=htmlpage&page=about [Online; accessed 08.08.2020].

Avelino, F., Grin, J., Pel, B., and Jhagroe, S. (2016). The politics of sustainability transitions. *Journal of Environmental Policy & Planning*, 18(5):557–567.

Bentivoglio, D. and Rasetti, M. (2015). Biofuel sustainability: review of implications for land use and food price. *Italian Review of Agricultural Economics*, 70(1):7–31.

Blok, K., Afanador, A., Van Der Hoorn, I., Berg, T., Edelenbosch, O. Y., and Van Vuuren, D. P. (2020). Assessment of sectoral greenhouse gas emission reduction potentials for 2030. *Energies*, 13(4):943.

Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G. J., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Loschel, A., et al. (2015). Assessing transformation pathways. in: Climate change 2014: Mitigation of climate change. contribution of working group iii to the fifth assessment report of the intergovernmental panel on climate change. Technical report, Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Cubasch, U., Meehl, G., Boer, G., Stouffer, R., Dix, M., Noda, A., Senior, C., Raper, S., and Yap, K. (2001). Projections of future climate change. In *Climate Change 2001: The scientific basis. Contribution of WG1 to the Third Assessment Report of the IPCC (TAR)*, pages 525–582. Cambridge University Press.

Doran, P. T. and Zimmerman, M. K. (2009). Examining the scientific consensus on climate change. *Eos, Transactions American Geophysical Union*, 90(3):22–23.

Duchin, F. (2017). Climate optimism gets a road map: An ambitious plan to leverage existing solutions to global warming is short on analytic rigor.

Enviros, S. (2012). Phase down of hfc consumption in the eu-assessment of implications for the rac sector. *Executive summary*.

European Union (2014). *Final Report Summary - AMPERE (Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates)*. https://cordis.europa.eu/project/id/265139/reporting [Online; accessed 11.06.2020].

Friedlingstein, P., Solomon, S., Plattner, G., Knutti, R., Ciais, P., and Raupach, M. (2011). Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nature Climate Change*, 1(9):457–461.

Frischmann, C., Yussuff, A., Gouveia, J., Mangotra, A., Gentry, D., Metz, P., Forest, C., Wartenberg, A., Anand, C., Jafary, M., and Mehra, M. (2020). *The Drawdown Review (2020) - Climate Solutions for a New Decade*.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y., and Kainuma, M. (2017). SSP3: AIM implementation of shared socioeconomic pathways. *Global Environmental Change*, 42:268–283.

GHG Protocol (2014). Required greenhouse gases in inventories: Accounting and reporting standard amendment.

Global Carbon Budget (2018). *Shared Socioeconomic Pathways (SSPs)*. https://www.globalcarbonproject.org/carbonbudget/archive/2018/GCP_CarbonBudget_2018.pdf?fbclid=IwAR2xN5jHrbhxTI78ES9Olee54q1XwoQeBXOOkAGTiQRujgVugaDwF573SOg [Online; accessed 05.08.2020].

Hare, B., Brecha, R., and Schaeffer, M. (2018). Integrated assessment models: What are they and how do they arrive at their conclusions. *Clim. Anal*, pages 1–12.

Hawken, P., Wilkinson, K., Frischmann, C., Allard, R., Bayuk, K., Gouveia, J., Mehra, M., Toensmeier, E., and Chissel, C. (2017). *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*.

Investopedia (2019). *How Much of Airlines' Revenue Comes From Business Travelers?* https://www.investopedia.com/ask/answers/041315/how-much-revenue-airline-industry-comes-business-travelers-compared-leisure-travelers.asp#:~:text=key%20takeaways,stops%20or%20premium%2Dsection%20seats. [Online; accessed 18.05.2020].

IPCC (2014). *Climate Change 2014: Synthesis Report*. IPCC.

IPCC (2018). *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, Sustainable Development, and Efforts to Eradicate Poverty*. IPCC.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K. L., Kram, T., Riahi, K., Winkler, H., and Van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change*, 122(3):401–414.

Lamarque, J.-F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S. J., van Vuuren, D. P., Conley, A. J., and Vitt, F. (2011). Global and regional evolution of short-lived radiatively-active gases and aerosols in the representative concentration pathways. *Climatic change*, 109(1-2):191.

Ludwig, F., Terwisscha van Scheltinga, C., Verhagen, J., Kruijt, B., van Ierland, E., Dellink, R., de Bruin, H., and Kabat, P. (2007). Climate change impacts on developing countries - eu accountability. pages 1–45.

Mayer, A. L. and Rietkerk, M. (2004). The dynamic regime concept for ecosystem management and restoration. *BioScience*, 54(11):1013–1020.

NCHRP (2012). *Long-Distance and Rural Travel Transferable Parameters for Statewide Trabel Forecasting Models*.

Olivier, J. G. and Peters, J. (2019). Trends in global co2 and total greenhouse gas emissions: 2019 report. *PBL Netherlands Environmental Assessment Agency*.

Olivier, J. G., Schure, K., and Peters, J. (2017). Trends in global co2 and total greenhouse gas emissions: 2017 report. *PBL Netherlands Environmental Assessment Agency*, 5.

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., and van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic change*, 122(3):387–400.

PBL (2020). *IMAGE framework/IMAGE 3.0 in a nutshell*. `https://models.pbl.nl/image/index.php/IMAGE_framework/IMAGE_3.0_in_a_nutshell#Spatial_resolution` [Online; accessed 11.06.2020].

Project Drawdown (2020a). *Alternative Cement*. `https://www.drawdown.org/solutions/alternative-cement` [Online; accessed 14.07.2020].

Project Drawdown (2020b). *Bioplastics*. `https://www.drawdown.org/solutions/bioplastics` [Online; accessed 14.07.2020].

Project Drawdown (2020c). *Building Retrofitting*. `https://www.drawdown.org/solutions/building-retrofitting` [Online; accessed 14.07.2020].

Project Drawdown (2020d). *Carpooling*. `https://www.drawdown.org/solutions/carpooling` [Online; accessed 14.07.2020].

Project Drawdown (2020e). *District Heating*. `https://www.drawdown.org/solutions/district-heating` [Online; accessed 14.07.2020].

Project Drawdown (2020f). *Drawdown 2020*. `https://www.drawdown.org/` [Online; accessed 12.07.2020].

Project Drawdown (2020g). *Efficient aviation*. `https://www.drawdown.org/solutions/efficient-aviation` [Online; accessed 14.07.2020].

Project Drawdown (2020h). *Efficient Ocean Shipping*. `https://www.drawdown.org/solutions/efficient-ocean-shipping` [Online; accessed 14.07.2020].

Project Drawdown (2020i). *Efficient Trucks*. `https://www.drawdown.org/solutions/efficient-trucks` [Online; accessed 14.07.2020].

Project Drawdown (2020j). *Electric Cars*. `https://www.drawdown.org/solutions/electric-cars` [Online; accessed 13.07.2020].

Project Drawdown (2020k). *Electric Trains*. `https://www.drawdown.org/solutions/electric-trains` [Online; accessed 14.07.2020].

Project Drawdown (2020l). *Grid Flexibility*. `https://www.drawdown.org/solutions/grid-flexibility/technical-summary` [Online; accessed 02.07.2020].

Project Drawdown (2020m). *Health & Education*. `https://www.drawdown.org/solutions/health-and-education` [Online; accessed 10.08.2020].

Project Drawdown (2020n). *High-Efficiency Heat Pumps*. `https://www.drawdown.org/solutions/high-efficiency-heat-pumps` [Online; accessed 14.07.2020].

Project Drawdown (2020o). *High-Speed Rail*. https://www.drawdown.org/solutions/high-speed-rail [Online; accessed 14.07.2020].

Project Drawdown (2020p). *Improved Clean Cookstoves*. https://www.drawdown.org/solutions/improved-clean-cookstoves [Online; accessed 14.07.2020].

Project Drawdown (2020q). *Methane Digesters*. https://www.drawdown.org/solutions/methane-digesters [Online; accessed 14.07.2020].

Project Drawdown (2020r). *Public Transit*. https://www.drawdown.org/solutions/public-transit [Online; accessed 13.07.2020].

Project Drawdown (2020s). *Recycling*. https://www.drawdown.org/solutions/recycling [Online; accessed 14.07.2020].

Project Drawdown (2020t). *Smart Thermostats*. https://www.drawdown.org/solutions/smart-thermostats [Online; accessed 14.07.2020].

Project Drawdown (2020u). *Telepresence*. https://www.drawdown.org/solutions/telepresence [Online; accessed 14.07.2020].

Project Drawdown (2020v). *Utility-Scale Energy Storage*. https://www.drawdown.org/solutions/utility-scale-energy-storage/technical-summary [Online; accessed 02.07.2020].

Roelfsema, M., Fekete, H., Höhne, N., den Elzen, M., Forsell, N., Kuramochi, T., de Coninck, H., and van Vuuren, D. P. (2018). Reducing global ghg emissions by replicating successful sector examples: the 'good practice policies' scenario. *Climate Policy*, 18(9):1103–1113.

Roestenberg, B. (2015). *Energetische efficiëntie: COP zegt niet alles*. https://www.vakbladwarmtepompen.nl/techniek/artikel/2018/11/energetische-efficientie-cop-zegt-niet-alles-1013993 [Online; accessed 07.08.2020].

Science Based Targets Initiative (2014). Sectoral decarbonization approach (sda): A method for setting corporate emission reduction targets in line with climate science - draft for public consultation.

Sitra Studies (2015). *Green to Scale: Low-carbon success stories to inspire the world.*

Stehfest, E., van Vuuren, D., Bouwman, L., and Kram, T. (2014). *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. Netherlands Environmental Assessment Agency (PBL).

Trenberth, K. E., Marquis, M., and Zebiak, S. (2016). The vital need for a climate information system. *Nature Climate Change*, 6(12):1057–1059.

UN (2019). *New partnerships to save billions from ill effects of dirty fuels*. https://www.un.org/development/desa/en/news/sustainable/new-partnerships-to-save-billions-from-ill-effects-of-dirty-fuels.html [Online; accessed 28.07.2020].

UNFCCC, V. (2015). Adoption of the paris agreement. *I: Proposal by the President (Draft Decision), United Nations Office, Geneva (Switzerland)*, (s 32).

Van Vuuren, D. P., Den Elzen, M. G., Lucas, P. L., Eickhout, B., Strengers, B. J., Van Ruijven, B., Wonink, S., and Van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic change*, 81(2):119–159.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., et al. (2011). The representative concentration pathways: an overview. *Climatic change*, 109(1-2):5.

Van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., et al. (2014). A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change*, 122(3):373–386.

Van Vuuren, D. P. and Stehfest, E. (2013). If climate action becomes urgent: the importance of response times for various climate strategies. *Climatic change*, 121(3):473–486.

Van Vuuren, D. P., Stehfest, E., Gernaat, D. E., Van Den Berg, M., Bijl, D. L., De Boer, H. S., Daioglou, V., Doelman, J. C., Edelenbosch, O. Y., Harmsen, M., et al. (2018). Alternative pathways to the 1.5 c target reduce the need for negative emission technologies. *Nature climate change*, 8(5):391–397.

7 Appendix

7.1 Appendix A: List of Project Drawdown mitigation measures

Table 7: All climate mitigation measures included in the study Project Drawdown, in alphabetical order. Reduction potentials are given in cumulative $GtCO_2$ over the study period 2020 - 2050, as provided by Project Drawdown (2020).

Measure	**Scenario 1 reduction ($GtCO_2$)**	**Scenario 2 reduction ($GtCO_2$)**	**Short elaboration**
Abandoned Farmland Restoration	12.48	20.32	"A set of processes for restoring degraded, abandoned land to productivity and biosequestration."
Alternative Cement	7.98	16.10	"The partial replacement of clinker with alternative materials (such as fly ash, slag, natural pozzolans, and calcined clays) to reduce the quantity of clinker in ordinary portland cement systems. Additionally, alternative cements as a solution includes efficiency upgrades to cement plants that produce clinker, reducing its carbon intensity."
Alternative Refrigerants	43.53	50.53	"The gradual replacement of hydrofluorocarbons (HFCs) used in a variety of applications by alternative refrigerants with significantly lower global warming potential (GWP) including ammonia, carbon dioxide, propane and isobutane among others."
Bamboo Production	8.27	21.31	"The large-scale cultivation of bamboo production for timber or other biomass uses on degraded land, which sequesters carbon in soils, biomass and long-lived bamboo production products."
Bicycle Infrastructure	2.56	6.65	"The increased installation of bicycle paths to encourage more bicycle usage in urban environments. "
Biochar Production	2.22	4.39	"A biosequestration process for converting biomass to long-lived charcoal (and energy) which can be used as a soil amendment."
Biogas for Cooking	4.65	9.70	"Methane digester technologies that produce biogas for household heating through the anaerobic digestion of organic waste."
Biomass Power	2.52	3.57	"The use of perennial biomass feedstock for dedicated electricity generation and combined heat and power generation."
Bioplastics	0.96	3.80	"Replacing petroleum-based plastics with biomass feedstock-based plastic materials (also referred to as biopolymers)."
Building Automation Systems	6.47	10.48	"Automated control systems that can regulate a building's heating and cooling, lighting, appliances, and more to maximize energy efficiency and/or worker productivity."
Building Retrofitting	-	-	"The renovation of building components (including building envelope, appliances, and controls) to include high-efficiency solutions."
Carpooling	7.70	4.17	"Increasing urban car occupancy worldwide."

Continued on next page

Table 7 – *Continued from previous page*

Measure	Scenario 1 reduction ($GtCO_2$)	Scenario 2 reduction ($GtCO_2$)	Short elaboration
Coastal Wetland Protection	0.99	1.45	"The legal protection of carbon-rich mangroves, seagrasses, and saltmarshes, leading to reduced degradation rates and the safeguarding of carbon sinks."
Coastal Wetland Restoration	0.77	1.01	"Recovers coastal wetlands ecosystems capacity as carbon sinks."
Composting	2.14	3.13	"The conversion of biodegradable waste to a useful soil amendment, while avoiding emissions from landfills."
Concentrated Solar Power	18.60	23.96	"An electricity generation technology that uses heat provided by direct normal solar irradiance concentrated on a small area, with and without storage."
Conservation Agriculture	13.40	9.43	"An annual crop production system that provides biosequestration via crop rotation, cover cropping, and reduced tillage."
Distributed Energy Storage	-	-	"Decentralized energy storage systems generally based on battery storage."
Distributed Solar Photovoltaics	27.98	68.64	"Systems that typically are sited on rooftops, that include both residential solar PV and community-scale solar PV systems with under 1 megawatt of capacity."
District Heating	6.28	9.85	"A centralized renewably-powered heating system and the distribution of generated heat to the buildings of a defined community, through a network of insulated buried pipes, to satisfy the demand for space heating."
Dynamic Glass	0.29	0.47	"Glass that dynamically changes its opacity to reduce or increase the amount of light and heat that is allowed to pass through."
Efficient Aviation	6.27	9.18	"The increased use of technologies to reduce aircraft fuel burn."
Efficient Ocean Shipping	4.40	6.30	"The use of technologies to make maritime shipping less fuel-intensive."
Efficient Trucks	4.61	9.71	"The increased use of fuel reduction technologies and approaches for trucking."
Electric Bicycles	1.31	4.07	"The increased use of electric bicycles for urban travel."
Electric Cars	11.87	15.68	"The increased use of battery and plug-in hybrid cars, sport utility vehicles (SUV's) and light trucks."
Electric Trains	0.10	0.65	"The increased electrification of freight railways."
Farm Irrigation Efficiency	1.13	2.07	"A set of energy-efficient irrigation practices that increase crop yields while reducing emissions."
Forest Protection	5.52	8.75	"The legal protection of forest lands, leading to reduced deforestation rates and the safeguarding of carbon sinks."

Continued on next page

Table 7 – *Continued from previous page*

Measure	Scenario 1 reduction ($GtCO_2$)	Scenario 2 reduction ($GtCO_2$)	Short elaboration
Geothermal Power	6.19	9.85	"Geothermal systems for electricity generation, combining both mature technologies and future expectations for enhanced geothermal."
Grassland Protection	3.35	4.25	"The legal protection of natural, ungrazed grasslands from future grazing and/or conversion to annual cropland, perennial cropland, biomass or bioenergy crops."
Green and Cool Roofs	0.60	1.10	"Building roofs that use light reflecting materials or paints and building roofs with natural vegetation."
Grid Flexibility	-	-	"A portfolio of practices and technologies (System Operation, Markets, Load, Flexible Generation, Networks, and Storage) that increase grid efficiency, resilience, and ability to integrate variable renewable energy sources."
Health and Education	85.42	85.42	"The influence of two rights-based solutions on global population: universal education and family planning. Increased access to and quality of voluntary reproductive healthcare, family planning resources, and 12-13 years of schooling are essential components to achieve the United Nations' 2015 medium global population projection of 9.7 billion people by 2050."
High-Efficiency Heat Pumps	4.16	9.29	"High-efficiency electrical devices that harvest latent heat from ambient sources such as the ground, air, or water for use in the conditioned space via the compression and expansion of a working fluid (refrigerant)."
High-Performance Glass	10.04	12.63	"Any of several mature static glass technologies that can reduce heat flow across the glass including multiple layers, low-emissivity glass, tinted glass, and vacuum glazing."
High-Speed Rail	1.30	3.77	"Track construction for increased use of high-speed rail for intercity travel."
Hybrid Cars	7.89	4.63	"The increased use of hybrid cars (not plug-in hybrids)."
Improved Clean Cookstoves	31.34	72.65	"Solar-powered or fuel-burning household stoves that reduce greenhouse gas emissions by either increasing thermal efficiency, reducing specific emissions, or increasing ventilation."
Improved Rice Production	9.44	13.82	"A set of practices to reduce methane emissions from paddy rice production using alternate wet and dry periods and other strategies."
Indigenous Peoples' Forest Tenure	8.69	12.93	"Providing indigenous communities with secure legal tenure rights to their traditional forest land."
Insulation	16.97	19.01	"The use of high levels of improved materials in building envelopes that resist heat flow and regulate indoor temperatures."

Continued on next page

Table 7 – *Continued from previous page*

Measure	Scenario 1 reduction ($GtCO_2$)	Scenario 2 reduction ($GtCO_2$)	Short elaboration
Landfill Methane Capture	2.18	-1.60	"The process of capturing methane generated from anaerobic digestion of municipal solid waste in landfills and incinerating the captured biogas to generate electricity."
LED Lighting	16.07	17.53	"The use of efficient light-emitting diodes (LEDs) in commercial or residential buildings."
Low-Flow Fixtures	0.91	1.56	"The use of low-flow showers and taps in the household."
Managed Grazing	16.42	26.01	"A set of practices that sequester carbon in grassland soils by adjusting stocking rates, timing, and intensity of grazing. "
Methane Digesters	9.83	6.18	"Systems associated with agriculture, manure, and wastewater facilities that produce biogas to be used for electricity generation in dedicated biogas or combined heat and power plants."
Micro Wind Turbines	0.09	0.13	"Electricity-generating onshore wind turbines with capacity of 100 kilowatts or less."
Microgrids	-	-	"Localized groupings of electricity sources and loads that normally operate connected to and synchronously with the traditional centralized power grid, but can disconnect and function autonomously as physical and/or economic conditions dictate."
Multistrata Agroforestry	11.30	20.40	"A perennial cropping system featuring multiple layers of trees and other perennial crops, with high biosequestration impacts."
Net-Zero Buildings	-	-	"New buildings that utilize high-efficiency building solutions and on-site renewable energy systems to consume zero energy from utility-scale sources and produce net zero carbon emissions on an annual basis."
Nuclear Power	2.65	3.23	"The electricity generation from nuclear fission in the form of Uranium 235 as used in pressurized water reactors, a type of light-water reactor using low-enriched uranium fuel."
Nutrient Management	2.34	12.06	"Fertilizer application practices that use right source, right rate, right time and right placement principles"
Ocean Power	1.38	1.38	"Wave energy converters and tidal systems for electricity generation."
Offshore Wind Turbines	10.44	11.42	"Offshore utility-scale wind power technologies."
Onshore Wind Turbines	47.21	147.72	"Onshore utility-scale wind power technologies."

Continued on next page

Table 7 – *Continued from previous page*

Measure	**Scenario 1 reduction ($GtCO_2$)**	**Scenario 2 reduction ($GtCO_2$)**	**Short elaboration**
Peatland Protection and Rewetting	26.03	41.93	"The protection of carbon-rich peatlands, leading to reduced degradation rates and the safeguarding of carbon sinks as well as restoration (largely through rewetting) and protection of the currently degraded peatlands."
Perennial Biomass Production	4.00	7.04	"The use of perennial grasses and coppiced woody plants for bioenergy feedstock, instead of annual crops like corn."
Perennial Staple Crops	15.45	31.26	"The production of trees and other perennial crops for staple protein, fats, and starch."
Plant-Rich Diets	65.01	91.72	"The individual dietary choice: to 1) maintain a 2250 calorie per day nutritional regime; 2) meet daily protein requirements while decreasing meat consumption in favor of plant-based food items; and 3) purchase locally produced food when available."
Public Transit	7.51	23.36	"The increased usage of mass transit or public transport to get around cities. "
Recycled Paper	1.10	1.95	"The increased recovery and reprocessing of used paper into paper products."
Recycling	5.50	6.02	"The increased recovery of recyclable materials, not including paper nor organic materials, from the industrial and residential sectors of the economy."
Reduced Food Waste	87.45	94.56	"Minimizing food loss and wastage from all stages of production, distribution, retail, and consumption."
Refrigerant Management	57.75	57.75	"Controlling leakages of refrigerants from existing appliances through better management practices and recovery, recycling, and destruction of refrigerants at the end of life."
Regenerative Annual Cropping	14.52	22.27	"Any annual cropping system that includes at least four of the following six practices: compost application, cover crops, crop rotation, green manures, no-till or reduced tillage, and/or organic production."
Silvopasture	26.58	42.31	"The addition of trees to pastures for increased productivity and biosequestration."
Small Hydropower	1.69	3.28	"Small-scale hydropower technologies under 10 megawatts, including in-stream hydrokinetic systems."
Smart Thermostats	6.99	7.40	"Internet-connected devices in households that reduce the heating and cooling demand of homes by using sensors and intelligent settings to maintain building comfort."
Solar Hot Water	3.59	14.29	"The use of solar radiation to pre-heat or heat water for residential use within buildings."

Continued on next page

Table 7 – *Continued from previous page*

Measure	**Scenario 1 reduction ($GtCO_2$)**	**Scenario 2 reduction ($GtCO_2$)**	**Short elaboration**
Sustainable Intensification for Smallholders	1.36	0.68	"Reduces emissions from three sustainable intensification practices: agroecological pest management, crop diversification (integrated crop-livestock system), and capacity building (access to knowledge, training, finance etc.)."
System of Rice Intensification	2.78	4.26	"Planting single seedlings with more space between them, rather than by the handful and bunched closely together; Watering intermittently and allowing for dry spells, rather than using continuous flooding; Tending plots with a rotating hoe, to address weeds and aerate soil, and applying compost."
Telepresence	1.05	3.80	"Replacing flying for business meetings with telepresence technologies."
Temperate Forest Restoration	19.42	27.85	"The restoration and protection of temperate-climate forests on degraded lands. "
Tree Intercropping	15.03	24.40	"A suite of agroforestry systems that deliberately grow trees together with annual crops in a given area at the same time."
Tree Plantations (on Degraded Land)	22.24	35.94	"The cultivation of trees for timber or other biomass uses on degraded land."
Tropical Forest Restoration	54.45	85.14	"The restoration and protection of tropical-climate forests."
Utility-Scale Energy Storage	-	-	"New technologies and practices to store energy on a utility level."
Utility-Scale Solar Photovoltaics	42.32	119.13	"Solar photovoltaic (PV) systems bigger than 10MW used for electricity generation."
Walkable Cities	1.44	5.45	"Designing and retrofitting urban environments to encourage walking for commuting or transportation."
Waste-to-Energy	2.04	3	"The combustion of waste and conversion to electricity and usable heat in waste-to-energy plants."
Water Distribution Efficiency	0.66	0.94	"Reducing water leakage or oversupply of regional water, which reduces pumping and pressurisation electricity and associated greenhouse gas emissions."

7.2 Appendix B: Replicability heatmap of Project Drawdown's measures

Table 8: Visualisation of the replicability of Project Drawdown measures in IMAGE, including the net reduction potential in 2050 per measure (GtCO$_2$-equivalent) and the contribution to the total net reduction potential (%).

Mitigation measures per sector	Scenario 1 reduction	Scenario 2 reduction
Electricity sector		
Biomass Power	0.2 Gt (0.3%)	0.2 Gt (0.2%)
Concentrated Solar Power	1.2 Gt (1.9%)	1.5 Gt (1.6%)
Distributed Energy Storage	0 Gt (0%)	0 Gt (0%)
Distributed Solar Photovoltaics	1.9 Gt (2.8%)	4.4 Gt (4.6%)
Geothermal Power	0.4 Gt (0.6%)	0.6 Gt (0.7%)
Grid Flexibility	0 Gt (0%)	0 Gt (0%)
Micro Wind Turbines	0 Gt (0%)	0 Gt (0%)
Microgrids	0 Gt (0%)	0 Gt (0%)
Nuclear Power	0.2 Gt (0.3%)	0.2 Gt (0.2%)
Ocean Power	0.1 Gt (0.1%)	0.1 Gt (0.1%)
Offshore Wind Turbines	0.7 Gt (1%)	0.7 Gt (0.8%)
Onshore Wind Turbines	3.1 Gt (4.7%)	9.4 Gt (9.8%)
Small Hydropower	0.1 Gt (0.2%)	0.2 Gt (0.2%)
Utility-Scale Energy Storage	0 Gt (0%)	0 Gt (0%)
Utility-Scale Solar Photovoltaics	2.8 Gt (4.2%)	7.6 Gt (7.9%)
Waste-to-Energy	0.1 Gt (0.2%)	0.2 Gt (0.2%)
Water Distribution Efficiency	0 Gt (0.1%)	0.1 Gt (0.1%)
Transport sector		
Bicycle infrastructure	0.2 Gt (0.3%)	0.4 Gt (0.4%)
Carpooling	0.5 Gt (0.8%)	0.3 Gt (0.3%)
Efficient Aviation	0.4 Gt (0.6%)	0.6 Gt (0.6%)
Efficient Ocean Shipping	0.3 Gt (0.4%)	0.4 Gt (0.4%)
Efficient Trucks	0.3 Gt (0.5%)	0.6 Gt (0.6%)
Electric Bicycles	0.1 Gt (0.1%)	0.3 Gt (0.3%)
Electric Cars	0.8 Gt (1.2%)	1 Gt (1%)
Electric Trains	0 Gt (0%)	0 Gt (0%)
High-Speed Rail	0.1 Gt (0.1%)	0.2 Gt (0.3%)
Hybrid Cars	0.5 Gt (0.8%)	0.3 Gt (0.3%)
Public Transit	0.5 Gt (0.8%)	1.5 Gt (1.6%)
Telepresence	0.1 Gt (0.1%)	0.2 Gt (0.3%)
Walkable Cities	0.1 Gt (0.1%)	0.3 Gt (0.4%)

Mitigation measures per sector	Scenario 1 reduction	Scenario 2 reduction
Residential		
Biogas for Cooking	0.3 Gt (0.5%)	0.6 Gt (0.6%)
Building Automation Systems	0.4 Gt (0.6%)	0.7 Gt (0.7%)
Building Retrofitting	0 Gt (0%)	0 Gt (0%)
District Heating	0.4 Gt (0.6%)	0.6 Gt (0.7%)
Dynamic Glass	0 Gt (0%)	0 Gt (0%)
Green and Cool Roofs	0 Gt (0.1%)	0.1 Gt (0.1%)
High-Efficiency Heat Pumps	0.3 Gt (0.4%)	0.6 Gt (0.6%)
High-Performance Glass	0.7 Gt (1%)	0.8 Gt (0.8%)
Improved Clean Cookstoves	2.1 Gt (3.1%)	4.6 Gt (4.8%)
Insulation	1.1 Gt (1.7%)	1.2 Gt (1.3%)
LED Lighting	1.1 Gt (1.6%)	1.1 Gt (1.2%)
Low-Flow Fixtures	0.1 Gt (0.1%)	0.1 Gt (0.1%)
Net-Zero Buildings	0 Gt (0%)	0 Gt (0%)
Smart thermostats	0.5 Gt (0.7%)	0.5 Gt (0.5%)
Solar Hot Water	0.2 Gt (0.4%)	0.9 Gt (1%)
Industry		
Alternative Cement	0.5 Gt (0.8%)	1 Gt (1.1%)
Bioplastics	0.1 Gt (0.1%)	0.2 Gt (0.3%)
Recycled Paper	0.1 Gt (0.1%)	0.1 Gt (0.1%)
Recycling	0.4 Gt (0.6%)	0.4 Gt (0.4%)
Non-CO_2		
Alternative Refrigerants	2.9 Gt (4.4%)	3.2 Gt (3.4%)
Composting	0.1 Gt (0.2%)	0.2 Gt (0.2%)
Landfill Methane Capture	0.1 Gt (0.2%)	-0.1 Gt (-0.1%)
Methane Digesters	0.7 Gt (1%)	0.4 Gt (0.4%)
Refrigerant Management	3.9 Gt (5.8%)	3.7 Gt (3.9%)
Health & Education		
Health and Education	5.7 Gt (8.6%)	5.4 Gt (5.7%)
Land		
Abandoned Farmland Restoration	0.8 Gt (1.3%)	1.3 Gt (1.4%)
Bamboo Production	0.6 Gt (0.8%)	1.4 Gt (1.4%)
Biochar Production	0.1 Gt (0.2%)	0.3 Gt (0.3%)
Coastal Wetland Protection	0.1 Gt (0.1%)	0.1 Gt (0.1%)

Mitigation measures per sector	Scenario 1 reduction	Scenario 2 reduction
Land (continued)		
Conservation Agriculture	0.9 Gt (1.3%)	0.6 Gt (0.6%)
Farm Irrigation Efficiency	0.1 Gt (0.1%)	0.1 Gt (0.1%)
Forest Protection	0.4 Gt (0.6%)	0.6 Gt (0.6%)
Grassland Protection	0.2 Gt (0.3%)	0.3 Gt (0.3%)
Improved Rice Production	0.6 Gt (0.9%)	0.9 Gt (0.9%)
Indigenous Peoples' Forest Tenure	0.6 Gt (0.9%)	0.8 Gt (0.9%)
Managed Grazing	1.1 Gt (1.6%)	1.6 Gt (1.7%)
Multistrata Agroforestry	0.8 Gt (1.1%)	1.3 Gt (1.4%)
Nutrient Management	0.2 Gt (0.2%)	0.8 Gt (0.8%)
Peatland Protection and Rewetting	1.7 Gt (2.6%)	2.7 Gt (2.8%)
Perennial Biomass Production	0.3 Gt (0.4%)	0.4 Gt (0.5%)
Perennial Staple Crops	1 Gt (1.5%)	2 Gt (2.1%)
Plant-Rich Diets	4.3 Gt (6.5%)	5.8 Gt (6.1%)
Reduced Food Waste	5.8 Gt (8.8%)	6 Gt (6.3%)
Regenerative Annual Cropping	1 Gt (1.5%)	1.4 Gt (1.5%)
Silvopasture	1.8 Gt (2.7%)	2.7 Gt (2.8%)
Sustainable Intensification for Smallholders	0.1 Gt (0.1%)	0 Gt (0%)
System of Rice Intensification	0.2 Gt (0.3%)	0.3 Gt (0.3%)
Temperate Forest Restoration	1.3 Gt (1.9%)	1.8 Gt (1.9%)
Tree Intercropping	1 Gt (1.5%)	1.5 Gt (1.6%)
Tree Plantations (On Degraded Land)	1.5 Gt (2.2%)	2.3 Gt (2.4%)
Tropical Forest Restoration	3.6 Gt (5.5%)	5.4 Gt (5.7%)

7.3 Appendix C: Residential emissions, based on averaged AMPERE projection

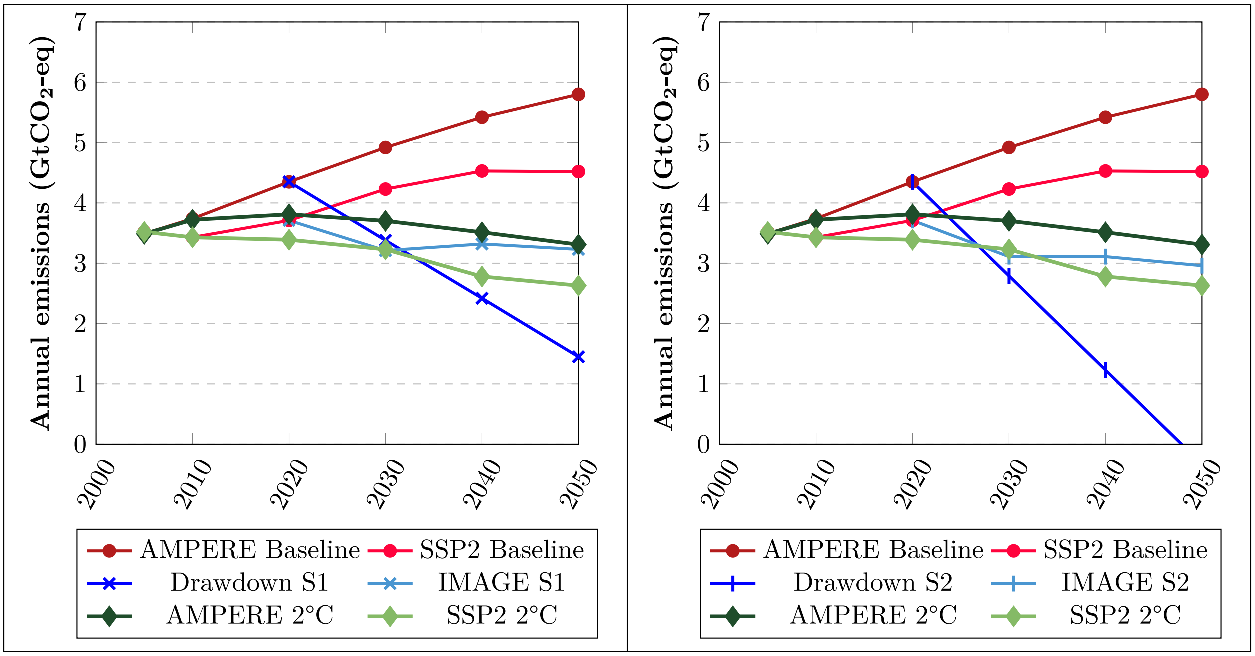

Figure 7.1: Annual emissions in the residential sector ($GtCO_2$-equivalent, including CO_2 and CH_4), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.

7.4 Appendix D: F-gas emissions, based on averaged AMPERE projection

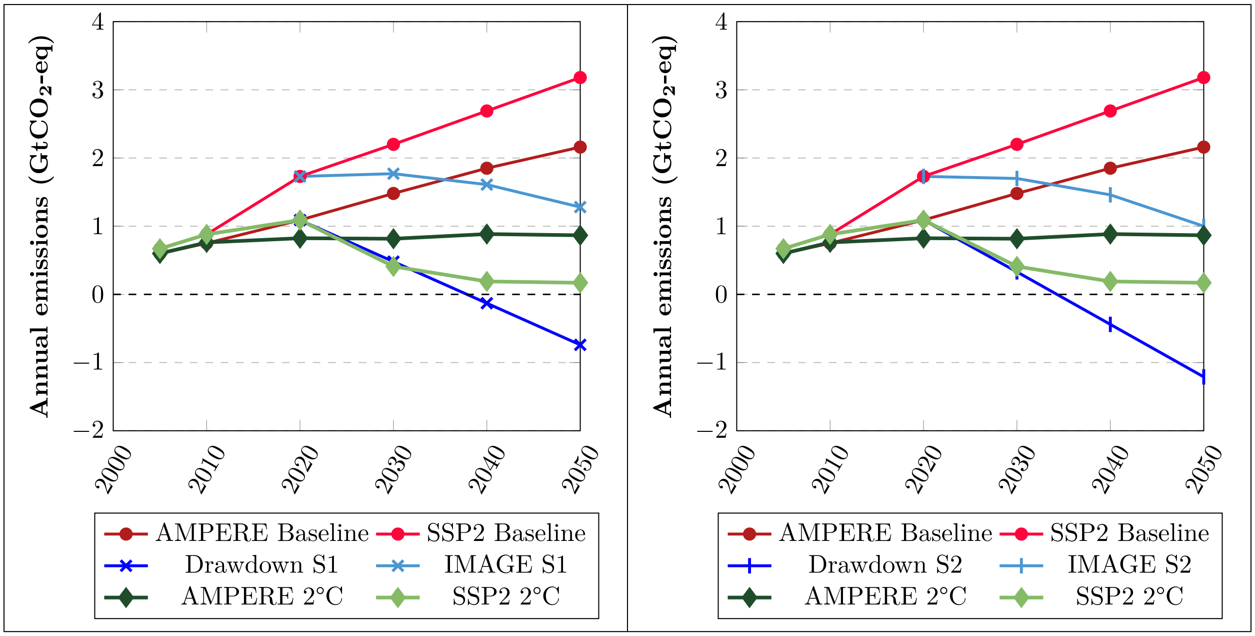

Figure 7.2: Annual emissions of F-gases ($GtCO_2$-equivalent), projected until 2050 for Drawdown and IMAGE mitigation Scenario 1 (left) and Scenario 2 (right), the AMPERE and SSP2 baselines and 2°C scenarios.