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Synergies and trade-offs between bioenergy use and the UN sustainable development goals

A quantitative approach using IMAGE model data to assess the impact of bioenergy use on indicators for the sustainable development goals related to bioenergy use by 2030

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SUSTAINABLE DEVELOPMENT GOALS

Abstract

In 2015 the United Nations adopted the sustainable development goals (SDGs) and the Paris agreement. The SDGs consist of 17 goals for a sustainable society, while the Paris agreement intends to limit anthropogenic climate change. Bioenergy is expected to play an important role in achievement of the Paris agreement, but can also affect progress towards multiple SDGs. In this research the possible synergies and trade-offs between bioenergy use and the SDGs in 2030 are quantified.

For this, IMAGE model projections are assessed using a newly set-up method. Multiple indicators are selected for SDGs related to bioenergy. The impact of bioenergy is quantified by comparing scenarios with bioenergy use allowed and a counterfactual without bioenergy. A composite indicator per SDG is created using the individual indicators and the desired direction of their change. Positive composite indicator results are defined as synergies between bioenergy use and the SDGs, negative results as trade-offs. Three alternative futures are assessed in a baseline and climate change scenario to compare differences in bioenergy implementation and use.

The results show that synergies and trade-offs between bioenergy use and the SDGs differ under alternative futures and scenarios. When allowing bioenergy use, in an optimistic (SSP1) and middle-of-the-road (SSP2) future, mostly synergies (up to 21%) occur. This is as bioenergy use lowers prices and, under the implementation methods in these futures, net total greenhouse gas emissions decline. In a pessimistic (SSP3) future, trade-offs (down to 3%) occur. This is as poor implementation of bioenergy in this future drives land use change, which results in a net increase of total greenhouse gas emissions by bioenergy use. With climate change mitigation the synergies and trade-offs are generally stronger compared to the baseline (difference up to 19 percent point between baseline and CCM). This is caused mainly by a difference in bioenergy competitiveness. With the implementation of carbon taxes in the CCM scenario, the competitiveness of bioenergy with other energy sources increases. Result is higher bioenergy demand and consequently exaggeration of the synergies and trade-offs. Due to model limitations, not for all related SDGs quantification of the indicators was possible. For these SDGs the impact of bioenergy use is assessed qualitatively.

In the current IMAGE model SDGs related to emissions and climate aspects are covered well, but SDGs related to social aspects require improvement. Suggestions for improvement are made and it is recommended to focus improvement efforts on socially related SDGs. The implementation method of bioenergy use has great impact to creation of synergies or trade-offs to the SDGs. Most important factor in prevention of trade-offs is prevention of natural land conversion. Further research to assess the impact of bioenergy use policies on the synergies and trade-offs may be necessary.

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Abbreviations

CCM	-	Climate Change Mitigation
CCS	-	Carbon Capture and Storage
FTE	-	Full-Time Equivalent
GBEP	-	Global BioEnergy Partnership
GCAM	-	Global Change Assessment Model
GDP	-	Gross Domestic Product
GHG	-	GreenHouse Gas
GWP	-	Global Warming Potential
HHI	-	Herfindahl-Hirschman Index
HTP	-	Human Toxicity Potential
IAM	-	Integrated Assessment Model
IEA	-	International Energy Agency
IMAGE	-	Integrated Model to Assess the Global Environment
IO	-	Input-Output
IPCC	-	International Panel on Climate Change
LPJmL	-	Lund-Potsdam-Jena model with Managed Lands
MAGNET	-	Modular Applied GeNeral Equilibrium Tool
SDG	-	Sustainable Development Goal
SRC	-	Short Rotation Coppice
SSP	-	Shared Socioeconomic Pathway
TIMER	-	The IMage Energy Regional model
TPES	-	Total Primary Energy Supply
UNFCCC	-	United Nations Framework Convention on Climate Change
WF	-	Water Footprint

1 Introduction

The current state of human society is unsustainable in many aspects. One example of an unsustainable environmental aspect is the impact of humans to the atmosphere where observations have shown a persistent increase in mean global temperatures (IPCC, 2014). Illustrating this is the definition of the current epoch as 'Anthropocene', a man made era, by geologists (Zalasiewicz et al., 2010). An example for a unsustainable social aspect is that that hunger has not been eradicated despite decades of efforts to prevent malnutrition (United Nations, 2015a).

Sustainable development goals

In order to move this unsustainable present state of society towards a sustainable future, the United Nations created the 2030 agenda for sustainable development (United Nations, 2015b). Formulated in the agenda are 17 sustainable development goals (SDGs) which together cover all parts of society (United Nations, 2015b). Each individual goal addresses multiple issues, for which separate targets are specified. This amounts to a combined total of 169 targets associated with the 17 SDGs. The goals are described in Box 1 and illustrated by the UN-issued poster in Figure 1. On 25 September 2015 all UN member states have signed the 2030 agenda for sustainable development, committing themselves to working towards full implementation of the SDGs by 2030 (United Nations, 2015b). Several SDGs are aimed at combating environmental unsustainability. SDG 13 (climate action) is aimed specifically at climate change mitigation, but acknowledges the United Nations Framework Convention on Climate Change (UNFCCC) as the primary forum for response to climate change (United Nations, 2015b).

Paris agreement and bioenergy

To combat climate change, the UNFCCC adopted the Paris agreement on 12 December 2015. With adoption of the Paris agreement, the member countries committed themselves to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' (UNFCCC, 2015). This is in response to the recognition of the International Panel on Climate Change (IPCC) that the overall effect of human activities has been of warming influence on the climate (IPCC, 2007). The increase of greenhouse gas (GHG) concentrations in the atmosphere since the start of the industrial era (about 1750) is recognised as the cause of the warming influence (IPCC, 2007). The burning of fossil fuels, which releases GHGs (mainly CO_2) to the atmosphere, is the largest known contributor to this effect (IPCC, 2007). If current trends are continued, the goal to limit global warming as set in the Paris agreement will not be met (IPCC, 2014). Implementation of policies for mitigation of climate change are thus required. Under these policies, CO_2 emissions as result of burning of fossil fuels should be avoided. One of the possible options to achieve this is the use of bioenergy. By uptake of CO_2 during biomass growth, net emissions from bioenergy burning are expected to be lower compared to emissions from bioenergy burning (Twidell & Weir, 2015). In projections of the future energy supply system, bioenergy is regarded as an indispensable energy source to achieve the Paris agreement goals (Cornelissen, Koper, & Deng, 2012). This might result in a future use of bioenergy increased by 50% from 2011 to 2035 (IEA, 2013).

Trade-offs and synergies

However, the use of bioenergy is expected to not only affect climate change (SDG 13), but also other aspects of society (De Bruin, 2016). Bioenergy production and use as required to meet the Paris agreement can be of positive contribution to some SDGs, while at the same time other SDGs are negatively affected (De Bruin, 2016). An example of this is that with an increase of bioenergy use, jobs in bioenergy crop production may be created (synergy with SDG8), but conversion of natural land to bioenergy cropland may also be necessary (trade-off with SDG15). This raises concerns that not both the Paris climate goal and all SDGs can be met at the same time if bioenergy is used (Müller et al., 2015; Stechow et al., 2016).

Relevancy and knowledge gap

The interactions between the SDGs and bioenergy use are thus relevant when making societal and policy choices. However, in current literature the relationship and interactions are only partially described. In the working paper of Müller et al. (2015), the impact of biomass (including food, feed and material use) on selected SDGs is described qualitatively. The report of Fritsche & Iriarte (2015) assesses the interactions between biomass and the SDGs for the EU only. The impact of multiple technology cases on the SDGs is assessed in the in the research of Stechow et al. (2016), which limited focus on bioenergy specifically. In the thesis of De Bruin (2016) the interactions between bioenergy and the SDGs are described qualitatively, but not quantitatively. Thus there is a gap in current knowledge, highlighting the need for a quantification of the effects between bioenergy use and the SDG. Next it is important to know how these may be affected by uncertainties concerning the future socioeconomic situation, and the effect of climate change mitigation policies.

Research questions & scope

The concerns raised above result in the main research question formulated as:

What are the trade-offs and synergies on the sustainable development goals by bioenergy use and how do the trade-offs and synergies change under implementation of a climate change mitigation goal?

For the SDGs affected by bioenergy use, indicators are selected. Next, the impact on these indicators of bioenergy use for different socioeconomic projections is assessed. For each scenario the impact of bioenergy use in both a baseline scenario and a climate change mitigation scenario is quantified. These results are compared to evaluate the consequences of climate change mitigation on the trade-offs and synergies. The temporal scope used in this research is set for 2030 as the SDGs are to be met in 2030. To provide deeper insight in the global results, a breakdown to five geographic regions (OECD90, reforming economies, Asia, Middle East and Africa, Latin America) is added.

In addition to the main research question, two additional sub questions are addressed. As no method to identify, quantify and analyse trade-offs and synergies between bioenergy and the SDGs exists in literature a method has been set up. This is formulated in the first sub question related to methodological aspects of this thesis:

How can trade-offs and synergies between sustainable development goals be assessed and quantified?

With the temporal scope of this research set in 2030, the used data are model projections. It if found that the used model (IMAGE) has difficulties in representing all SDGs related to bioenergy. This raised concerns on how well equipped the model is with relation to the SDGs. The second research sub question has thus been added:

How suitable is the IMAGE model for assessing the sustainable development goals and how can it be improved to better include the sustainable development goals?

With the answer to the second sub question recommendations are made to improve the model for more accurate inclusion of the SDGs.

Figure 1 – The 17 sustainable development goals (UN, 2016)

Sustainable development goals
1. End poverty in all its forms everywhere.
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3. Ensure healthy lives and promote well-being for all at all ages.
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
5. Achieve gender equality and empower all women and girls.
6. Ensure availability and sustainable management of water and sanitation for all.
7. Ensure access to affordable, reliable, sustainable and modern energy for all.
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10. Reduce inequality within and among countries.
11. Make cities and human settlements inclusive, safe, resilient and sustainable.
12. Ensure sustainable consumption and production patterns.
13. Take urgent action to combat climate change and its impacts.
14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss.
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
17. Strengthen the means of implementation and revitalize the Global Partnerships for Sustainable Development.

Box 1 – Description of the 17 sustainable development goals (United Nations, 2015b)

2 Methods

In this section the method used to assess trade-offs and synergies is constructed, in line with research sub question one. To provide structure and overview the construction of this method is broken down into the steps shown in Figure 2. The 'method' steps are discussed here, the results and discussion in section 3 and 4.
First, the SDGs relevant to bioenergy are selected (section 2.1). Parallel to this the model and scenarios that provide data are selected in section 2.2. With the model data available, indicators for the relevant SDGs are selected and the used method elaborated in section 2.3 and 2.4. Some SDGs are monitored by multiple indicators, so the method used to aggregate these indicator results into a single SDG result is explained in section 2.5. As a final step, synergies and trade-offs are defined in section 2.6.

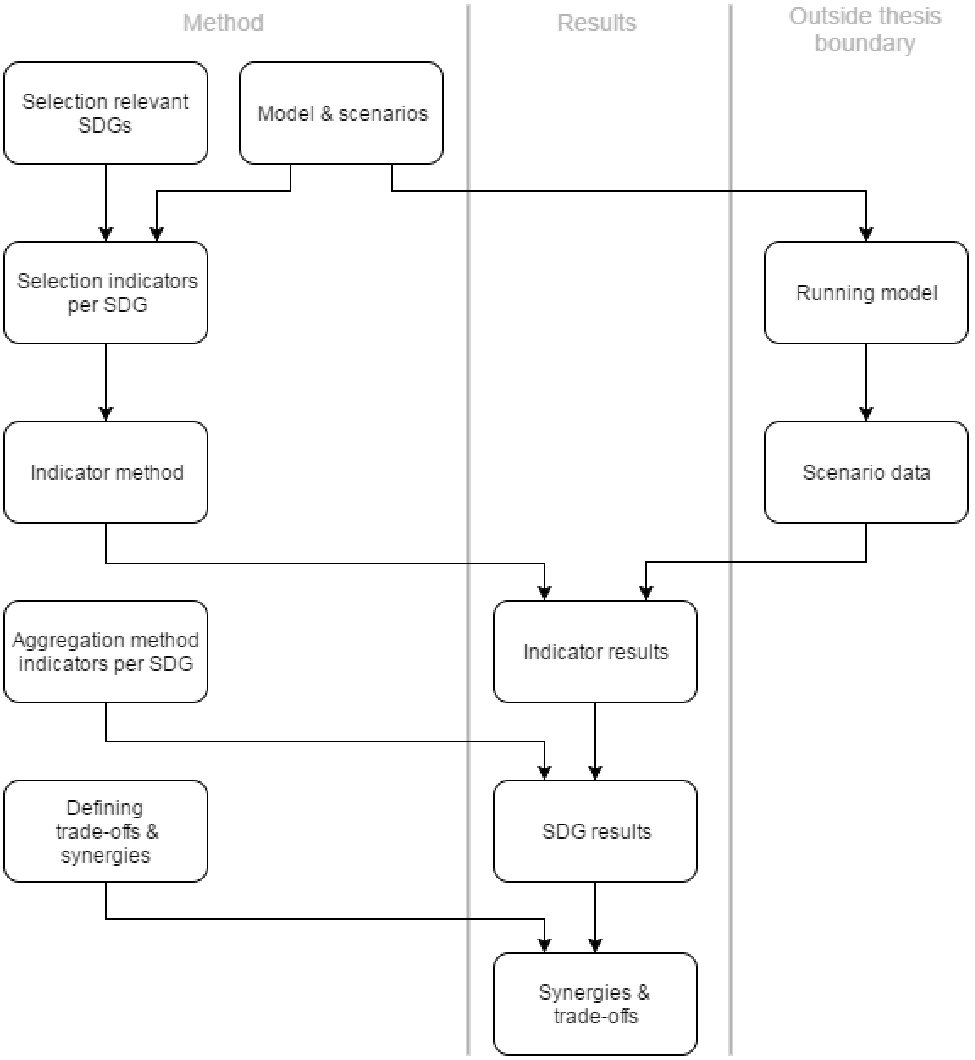

Figure 2 – Research workflow diagram

2.1 Selection relevant SDGs

To classify the relevancy of the SDGs to bioenergy the links as described in existing literature is used. De Bruin (2016) classifies the SDGs to three levels of importance (very important, important, not important). Müller et al. (2015) and Fritsche & Iriarte (2015) use one level which describes the role of biomass (including food and feed) and its links to SDGs. It is assumed to be equal to the very important level used by De Bruin (2016). An overview of the classifications used by the sources can be found in Table 1.

Table 1 – SDGs linked to bioenergy as described in literature

Source	Strong link	Intermediate link	Weak link
De Bruin (2016)	6 7 8 13 15	1 2 3 9 14 17	4 5 10 11 12 16
Müller et al. (2015)	2 7 9 12 13 15		
Fritsche & Iriarte (2015)	2 7 12 13 15		

Between the sources there is consensus on the strong link of SDG 7, 13 and 15 to bioenergy use. Although there is no consensus on the strong link of SDGs 2, 6 and 8 they are classified as strong links as bioenergy can have a strong impact on aspects covered in these goals (food supply, water use and employment). SDG 9 is regarded strongly linked by Müller et al. (2015) however the impact on this SDG is assumed to decrease when moving from biomass in general to bioenergy specially, therefore the intermediate link as De Bruin (2016) puts forward is used. The classification of SDG 12 as strongly linked by Müller et al. (2015) and Fritsche & Iriarte (2015) is assumed to be the result of inclusion of food and feed, as this consists of the largest part of biomass consumption. Dietary changes would thus have a great effect on responsible consumption, while for bioenergy the link is assumed to be low and therefore it is classified as weak.

The resulting classification of the SDGs into strong, intermediate and weak links to bioenergy in this thesis is presented in Table 2. For both the strong and intermediate levels an explanation per SDG is given below. SDGs with a weak link to bioenergy are further excluded from this research.

Table 2 - SDGs linked to bioenergy as used in this thesis

Strong link	Intermediate link	Weak link
2 – Zero hunger	1 – No poverty	4 – Quality education
6 – Clean water and sanitation	3 – Good health and well-being	5 – Gender equality
7 – Affordable and clean energy	9 – Industry, innovation and infrastructure	10 – Reduced inequalities
8 – Decent work and economic growth	14 – Life below water	11 – Sustainable cities and communities
13 – Climate action		12 – Responsible consumption and production
15 – Life on land		16 – Peace, justice and strong institutions
		17 – Partnership for the goals

Strong link

SDG 2 – Zero hunger

One possible unintended side effect of bioenergy use is the competition with food. The prevalence of hunger is related to food prices (Anríquez, Daidone, & Mane, 2013) which in turn could be affected by bioenergy use. This can be directly by using food crops for energy production or indirectly via agricultural land use competition. Although food competition is an important concern to bioenergy use there is yet no scientific consensus on the occurrence and magnitude (Serra & Zilberman, 2013).

SDG 6 – Clean water and sanitation

Water resources are globally under stress by water consumption of human activities (Seckler, Barker, & Amarasinghe, 1999). As bioenergy feedstock production requires significant amounts of water (Gerbens-Leenes, Hoekstra, & van der Meer, 2009) it is possible that bioenergy use increases water resource stress, as result less water will be available for other purposes such as drinking water and sanitation use.

SDG 7 – Affordable and clean energy

Bioenergy use can have a large influence on the energy system. First, it can help lower the environmental impacts of the energy system, assuming bioenergy is produced in a sustainable way with limited impact on land-based carbon stocks (Cornelissen et al., 2012). Secondly, energy prices can be affected by increased competition with other (renewable) energy sources. Via the price impact, the impact of bioenergy can propagate to many aspects of society such as freight, traditional biomass use and the energy intensity of society.

SDG 8 – Decent work and economic growth

Compared to other energy sources, bioenergy generally has a higher employment rate per unit energy supplied and can therefore create a substantial amount of jobs (Domac, Richards, & Risovic, 2005; Singh & Fehrs, 2001; UNEP, 2008; Wei, Patadia, & Kammen, 2010). Furthermore, for some regions it has the potential to substitute energy imports which affects economic growth and welfare (Domac et al., 2005).

SDG 13 – Climate action

In long term assessment, one of the main driver of bioenergy implementation is reduction of GHG emissions. The carbon released during bioenergy use is sequestered from the air during biomass growth, in theory making it a carbon neutral energy source. Even when including potential land use change emissions, it is expected that bioenergy use can be an important aspect of mitigation of climate change (Cornelissen et al., 2012; Daioglou, 2016). However, energy inputs for biomass production and soil organic carbon changes affect the net carbon emissions of bioenergy which result in varying degrees of climate impact and created a debate about the sustainability of bioenergy (Fargione et al., 2008; Searchinger et al., 2008).

SDG 15 – Life on land

Bioenergy production requires land area, which could promote conversion of natural land into agricultural land. Associated with conversion of natural land such as forests or grasslands is the loss of biodiversity and habitat of species (Newbold et al., 2015).

Intermediate link

SDG 1 – No poverty

In both developed and developing regions bioenergy can create employment, for developing regions in particular the employment can lift households out of poverty (Domac et al., 2005). As bioenergy can increase economic growth, it can also have an indirect positive effect for people living in poverty (Adams, 2004; Dollar, Kleineberg, & Kraay, 2016).

SDG 3 – Good health and well-being

Important aspects of SDG 3, for example maternal mortality rate and epidemic diseases, are assumed to be unaffected by bioenergy. Two mechanisms are distinguished by which bioenergy can impact health. First, agriculture is a known major contributor of non-GHG air pollution (Lelieveld et al., 2015). Agricultural activities for bioenergy production could therefore affect ambient air pollution. Secondly, energy prices will be affected by inclusion of bioenergy which could result in a shift towards fuels emitting less toxics.

SDG 9 – Industry, innovation and infrastructure

Bioenergy delivery and processing requires developed infrastructure networks, therefore extended bioenergy use could initiate infrastructure investments (De Bruin, 2016). Long-term economic development could also be improved by extending access to modern energy (De Bruin, 2016).

SDG 14 – Life below water

Fertilizer use for bioenergy production and chemicals used in conversion processes could end up in water streams where they can cause eutrophication and dead zones which harm underwater life (De Bruin, 2016).

2.2 Model and scenarios

As the temporal scope of this research is 2030 no empirical data is available. Instead a model is required to project future developments and calculate changes. As the SDGs address a wide range of issues and are not limited to a specific part of society or environment (e.g. economy, agriculture), the model is required to have the same wide coverage to incorporate all changes to the SDGs. The model used in this research is the Integrated Model to Assess the Global Environment (IMAGE) 3.0. The IMAGE model is selected for practical reasons, as its results are readily available and accessible. The IMAGE model is appropriate for use as it covers a broad spectrum of aspects so incorporates most SDGs. Furthermore IMAGE projections are used by internationally recognised bodies such as the IPCC and the United Nations Environmental Programme (Stehfest et al., 2014).

IMAGE model

IMAGE is a dynamic Integrated Assessment Model (IAM) framework to investigate the interactions between the natural environment and human development. IMAGE is characterised by relatively detailed biophysical and environmental processes. As illustrated by the model framework in Figure 3 population, economy developments and technological progress are drivers which IMAGE uses to project the implications for climate change, energy, land, water and more. Modules of the IMAGE framework of particular importance for this research are The Image Energy Regional model (TIMER) which projects the supply and demand of primary and secondary energy carriers (Van Vuuren et al., 2014), and the Modular Applied General Equilibrium Tool (MAGNET), which represents the agricultural economy. The trade-off between simplification and detail for the modules is safeguarded by calibration of each modules behaviour to historical data and projections of detailed single-issue models.

Bioenergy in IMAGE

Three modules within the IMAGE framework are interacting concerning biomass and bioenergy. Starting point is the demand for food and feed as calculated in the Modular Applied General Equilibrium Tool (MAGNET) module. This module is driven by the population and economic projections as set in the SSP scenarios and IMAGE calculations on land availability, suitability and yields. The demand for food and feed is translated to spatially explicit land use in the Lund-Potsdam-Jena model with Managed Lands (LPJmL) module. This module also allocates urban areas, bio-reserves (forests) and lands unsuitable for agriculture. The unassigned land after allocation is available for production of bioenergy feedstocks and combined with spatially explicit labour and capital costs to construct primary biomass supply curves. It is important to note that explicitly included with this approach is a food-first principle of land use.

The biomass supply curves are used together with supply curves of other energy sources and energy demand curves as inputs for The IMage Energy Regional (TIMER) module to determine the energy system. Energy demand is specified per sector for final energy use (gasses, liquids, solids, heat, electricity, hydrogen) while supply is specified to primary energy sources (coal, oil, natural gas, modern and traditional biomass, nuclear, solar, wind, hydro-power). TIMER takes into account a wide range of energy system aspects including energy carrier conversions where appropriate, carbon taxes, capital stock inertia and energy trade between regions to create cost-based competition between primary energy sources.

A more detailed description of IMAGE, the modules and the interactions can be found online (PBL, 2017).

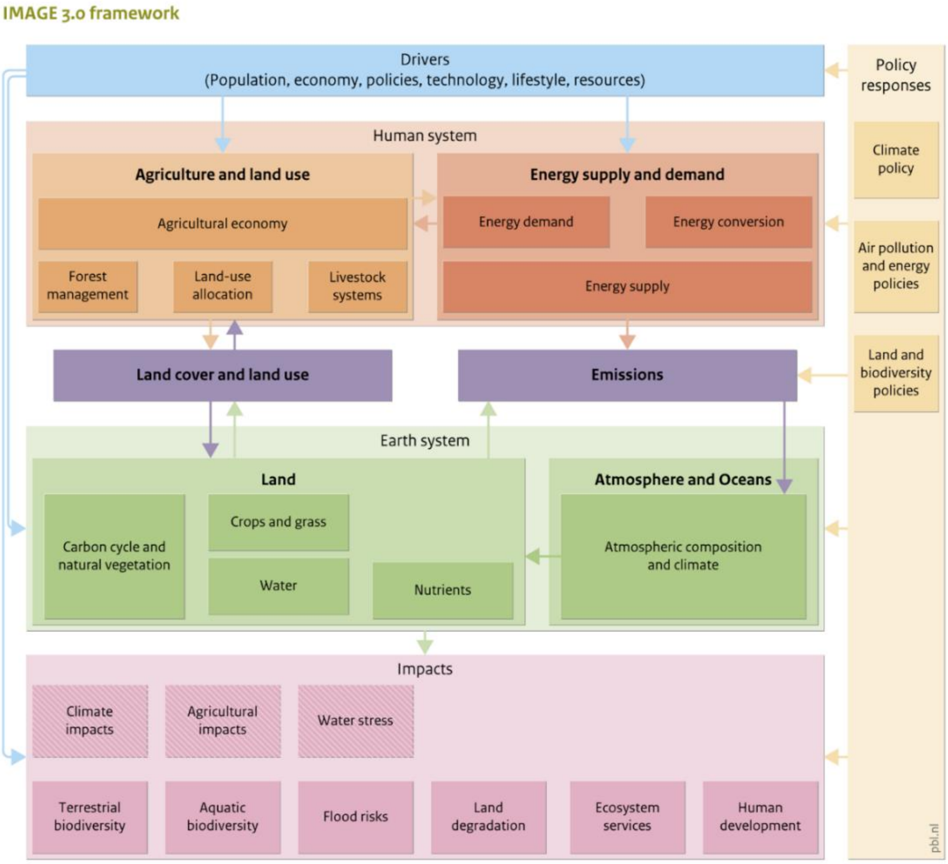

Figure 3 - IMAGE model framework (Stehfest et al., 2014)

SSP socioeconomic scenarios

The drivers for IMAGE are dependent on future developments and as these are uncertain, multiple sets of scenarios have been proposed to be used as drivers for model projections. The Shared Socioeconomic Pathways (SSPs) are a complete set of five alternative futures (SSP1 to SSP5) (O'Neill et al., 2017). SSP1, SSP2 and SSP3 are implemented in the IMAGE framework (Van Vuuren et al., 2015), a more detailed description of the scenarios is given in Box 2.

For each SSP four scenarios are implemented in IMAGE: a baseline, a baseline without bioenergy use, a climate change mitigation (CCM) scenario and a climate change mitigation scenario without bioenergy use. The scenarios without bioenergy use are set up to gradually phase out bioenergy. It is important to recognize that due to delays in stock turn-over and behavioural inertia included in the model, the phasing out is not complete till around 2070, so in 2030 some energy crops are still used in the scenarios without bioenergy.

For SSP1 and SSP2 with climate change mitigation the average solar radiative forcing is limited to 2.6 W/m^2 in the year 2100, for SSP3 there is no solution possible for this limit so the climate change mitigation scenario not included in this research (Van Vuuren et al., 2015). The mitigation is achieved by implementation of endogenously determined carbon taxes that are required to meet the radiative forcing target (Daioglou, 2016). The carbon tax levels are kept constant for the scenarios with climate change mitigation but without bioenergy use, making these scenarios miss the radiative forcing target (Daioglou, 2016). The combinations of SSPs and scenarios are represented in Table 3.

Table 3 – Scenario overview (combination of SSPs, bioenergy use and CCM)

Scenarios	SSP1	SSP2	SSP3
Baseline	●	●	●
Baseline without bioenergy	●	●	●
Mitigation to 2.6 W/m^2	●	●	
Mitigation to 2.6 W/m^2 without bioenergy	●	●	

SSP1 – Sustainability

This scenario assumes low population growth, fast technological advances, high international cooperation and strong institutions. Also included are cultural changes as dietary shift to lower meat consumption and a preference for renewable energy. Due to these assumptions SSP1 results in the least stress on the environment of the five SSP scenarios with low socio-economic challenges for adaption and mitigation as consequence.

SSP2 – Middle of the road

SSP set 2 is explicitly included as a middle of the road scenario. This scenario is based on historical social, economic and technological trends which can be considered medium in comparison with SSP1 and SSP3. This also results in medium socio-economic challenges for adaption and mitigation.

SSP3 – Regional rivalry

The third scenario assumes a world with isolated regions that set up trade barriers and hinder international cooperation, with as less technological and economic advances. This results in less welfare and education, keeping fertility rates high which steadily increases the world population. Energy intensities decline little since there is little technological progress and due to the preference of regions for energy self-sufficiency, the regions with large fossil fuel reserves remain carbon intensive. These combinations put a large stress on the environment, although the effect is dampened to some degree by the lower economic growth compared with SSP1 and SSP2. All this combined SSP3 results in high challenges for adaption and mitigation.

Box 2 - SSP scenario description (based on O'Neill et al. (2017))

2.3 Selection of indicators

For the 17 SDGs the UN has implemented 169 targets and a total of 230 proposed indicators (IAEG-SDG, 2015). However not all of these are unambiguous and useable for scientific research (Hák, Janoušková, & Moldan, 2016; ICSU - ISSC, 2015). Furthermore not all indicators are relevant with respect to bioenergy, while other relevant ones to bioenergy are not included. For indicator selection the criteria as set up in Dale et al. (2013) are used: indicators need to be practical, sensitive, unambiguous, anticipatory, predictive, estimable and sufficient. The practicality requirement is interpreted in this research as model data availability. Sensitivity dictates the indicator needs to be related to bioenergy and anticipatory that the indicator is expected to change with bioenergy use. Unambiguity, predictively and estimability safeguard correct interpretation of the indicator results. Sufficiency is regarded for the set of indicators per SDG, to ensure inclusion of all relevant aspects of the SDG but to avoid double counting. First the indicators as proposed by the UN (IAEG-SDG, 2015) are screened with the requirements. Additionally indicators used in existing research to monitor progress on the SDGs are assessed (OECD, 2016; Sachs et al., 2016). To include all indicators relevant to bioenergy also the sustainability indicators for bioenergy as set up by the Global Bioenergy Partnership (GBEP) are assessed (GBEP, 2011). For SDGs that lacked indicators after this or for important aspects that were not covered indicators have been added that are specific to this research. In Table 4 and Table 5 an overview of the indicators is presented.

Throughout section 2.3, unless noted otherwise when referencing to UN indicators the source is IAEG-SDG (2015) and to the GBEP the source is GBEP (2011).

Table 4 - Indicators strong linked SDGs

SDG	Indicator	Source[1]	Unit	Add. data[2]	Tier[3]	Pos. dev.[4]	Details
2	Food price	G	Index		II	-	Cereal (wheat, rice, maize, corn, millet, sorghum, barley, oats, rye) price index, 2005 baseline
	Cereal yield	S	t dm/ha/yr		II	+	Annual cereal (wheat, rice, maize, corn, millet, sorghum, barley, oats, rye) dry matter production per hectare
6	Water footprint	UN, S, G	km^3/yr	●	III	-	Green and blue water consumption in bioenergy feedstock production
7	GHG emissions per unit energy	S, G	Mt CO_2eq/EJ		I	-	100 yr CO_2 equivalent emissions per unit final energy use
	Share renewable energy	S	% of TPES		I	+	Biomass and non-biomass renewables share of TPES
	Energy price	O	US$2005/GJ		I	-	Electricity price in US dollar 2005 inflation corrected
	Traditional biomass use	UN, S, G	EJ/yr		I	-	Energy used as traditional biomass per year
	Energy supply diversity	G	Index		I	+	Herfindahl-Hirschman diversity index of energy supply
8	Employment	UN, S, G	FTE	●	III	+	Number of full-time equivalent jobs in bioenergy feedstock production
13	Non-renewable energy use	G	EJ/yr		I	-	Fossil and nuclear primary energy use per year
	GHG emissions	O	Mt CO_2eq/yr		I	-	Total emitted Kyoto gasses (100 yr CO_2 equivalent)
	Land use GHG emissions	G	Mt CO_2eq/EJ		I	-	Land use 100 yr CO_2 equivalent emissions per primary unit energy from bioenergy crops
	Energy related emissions per capita	S	t CO_2eq/ person/yr		I	-	Total 100 yr CO_2 equivalent emissions of energy supply sector per person
15	Forest area	UN, S, G	Million km^2		I	+	Forest as proportion of total land area
	Agricultural land area	G	Million km^2		I	-	Agricultural land as proportion of total land area
	Bioenergy production yield	G	GJ/ha/yr		III	+	Annual primary bioenergy production per unit land

[1] UN = IAEG-SDG (2015), S = Sachs et al. (2016), G = GBEP (2011), O = Other, relevant references/argumentation in indicator description

[2] Add. data: Additional literature data required in indicator method

[3] Tier: Indicator method classification used in section 2.4

[4] Pos. dev.: Positive development, indicator direction development which is regarded positive (i.e. + for higher is better, - for lower is better)

Table 5 - Indicators intermediate linked SDGs

SDG	**Indicator**	**Sources**[1]	**Unit**	**Add. data**[2]	**Tier**[3]	**Pos. dev.**[4]	**Details**
1	Poverty	UN, S	% of pop.		-	-	Not possible with IMAGE model and SSP scenarios
3	Non-GHG air pollutants	UN, G	HTP/yr		I	-	Human Toxicity Potential equivalent gas emissions
	Indoor smoke	UN, G	Million persons		II	-	Population using solid fuels
9	GHG emissions per unit added value	UN	Kg CO_2eq/ US$2005		I	-	100 yr CO_2 equivalent emissions per GDP in US dollar 2005 inflation corrected
	Freight	UN	ton*km/year		II	+	Annual freight volumes
14	Nutrient pollution	UN	M kg PO_4eq/yr	●	III	-	Yearly eutrophication potential from bioenergy crop cultivation

[1] UN = IAEG-SDG (2015), S = Sachs et al. (2016), G = GBEP (2011)

[2] Add. data: Additional literature data required in indicator method

[3] Tier: Indicator method classification used in section 2.4

[4] Pos. dev.: Positive development, indicator direction development which is regarded positive (i.e. + for higher is better, - for lower is better)

Strong link

SDG 2 – Zero hunger

The first UN indicators (2.1.1 to 2.2.2) for SDG 2 are related to the prevalence and the effects of undernourishment in different forms. Undernourishment ratio is also included in existing research (Sachs et al., 2016). As undernourishment data is not available in IMAGE, use of other indicators for SDG 2 is necessary.

Food price

Bioenergy use can impact food prices as farmers may be driven by economic incentives to switch from food crop to bioenergy crop cultivation or if food is used to convert to biofuels due to price levels or legislation (Serra & Zilberman, 2013). As indicator for these effects the price of national food baskets is used by the GBEP. The regions used in IMAGE include multiple countries, so national food basket prices are not available. Instead the price index of non-energy crops and livestock is calculated in IMAGE and selected as indicator.

Cereal yield

Another side-effect of bioenergy production can be that food production is pushed-out to lower quality soils, thereby lowering yields and endangering food supply. Food supply measured as net food production is an indicator by the GBEP. Cereal yield is used as indicator by Sachs et al. (2016). The average yield weighted by production of cereals (wheat, rice, maize, corn, millet, sorghum, barley, oats, rye) is available in the model and used as indicator for this effect.

SDG 6 – Clean water and sanitation

Water footprint

Freshwater withdrawal as proportion of available freshwater resources is UN indicator 6.4.2 and also used in existing research (Sachs et al., 2016). Water use for bioenergy production unrelated to resource availability is an indicator by the GBEP. Water availability is not modelled in IMAGE, therefore the water use unrelated to source or resource size is used as indicator.

SDG 7 – Affordable and clean energy

GHG emissions per unit energy

In energy related research GHG emissions per unit energy are widely used as indicator for the sustainability of energy production. This is illustrated by the inclusion in the GBEP indicators and it is used for SDG 7 in existing research (Sachs et al., 2016).

Share renewable energy

The renewable energy share of total energy use is UN indicator 7.2.1, included by the GBEP and used in existing research (OECD, 2016; Sachs et al., 2016). It illustrates a transition from reliance on fossil energy sources to a renewable energy supply.

Energy price

Energy prices are not included as indicator by the UN, the GBEP or in existing literature (OECD, 2016; Sachs et al., 2016). However, SDG goal 7.1 is formulated to '(…) ensure universal access to affordable, reliable and modern energy services' (United Nations, 2015b). Affordability is explicitly mentioned in this and although it is also a function of income, the energy price can give an indication on the magnitude of change caused by bioenergy use. The energy price (with electricity price as indicator) is therefore included in this research.

Traditional biomass use

Also included in SDG goal 7.1 is access to modern energy services. The UN proposes population with access to electricity as indicator and this is accepted in existing literature (OECD, 2016; Sachs et al., 2016). In the IMAGE model electrification rates depend on the storyline of each SSP scenario and are therefore unaffected by bioenergy. Irrespective of access, the use of electricity is affected by bioenergy availability due to increased diversity (see below). Included in IMAGE as output is traditional biomass use, in for example three-stone stoves. As moving away from traditional biomass could imply switching to either electricity, liquid or gaseous fuels which achieves goal 7.1, it is selected as indicator.

Energy supply diversity

Energy supply diversity is used as indicator by the GBEP. Energy supply diversity reflects the dependency on different energy sources. Diversity of energy supply creates an energy system that is more resilient to price and supply changes. A stable energy system is in line with SDG 7 to 'Ensure access to (…) reliable (…) energy for all.' (United Nations, 2015b).

SDG 8 – Decent work and economic growth

Employment

The UN proposes indicator 8.5.2 "Unemployment rate, by sex, age and persons with disabilities". Employment and unemployment rates are also used in existing literature for SDG 8 (OECD, 2016; Sachs et al., 2016). More specific to bioenergy the GBEP uses as indicator the number of jobs in the bioenergy sector. In IMAGE the labour force size is unavailable, therefore the number of jobs instead of (un)employment rate is in selected as indicator.

SDG 13 – Climate action

The UN proposed indicators for SDG 13 are disaster and environmental policy related since they recognize the UNFCCC as the primary forum for response to climate change (IAEG-SDG, 2015). Bioenergy use is assumed to have an effect on climate change instead of disasters or policy, thus climate change related indicators are selected.

Non-renewable energy use

Inclusion of bioenergy in the energy system is intended to decrease the use of non-renewable energy source. However bioenergy is not only competing with non-renewable sources but also with other renewable energy sources such as wind or solar. Change in non-renewable energy use is included as it shows if the desired substitution is occurring.

GHG emissions

Greenhouse gas emissions are recognized as a major driving force of climate change (IPCC, 2007). To represent all changes in emissions (whether from supply or demand side and direct or indirect) total GHG emissions are included as indicator.

Land use GHG emissions

The GBEP includes as sustainability indicator lifecycle GHG emissions. The method proposed by the GBEP uses total lifecycle emissions as indicator since with bioenergy the indirect emissions from land-use change are pivotal for net positive or negative emissions (Fargione et al., 2008; Searchinger et al., 2008). The land use GHG emissions from bioenergy are thus included as separate indicator, next to the direct emissions indicator in SDG 7.

Energy related emissions per capita

The energy related CO_2 emissions per capita indicator is used by Sachs et al. (2016). Bioenergy is able to change emissions from supply side as it is a renewable energy source, but can also change emissions due to energy demand by affecting energy prices. The energy related emissions per capita include both effects and is thus included.

SDG 15 – Life on land

Forest area

Proposed indicator 15.1.1 by the UN is forest area as proportion of total land area. In existing research the annual change in forest area (Sachs et al., 2016) and land-use change (GBEP, 2011) are included. Although formulated differently these are aimed at deforestation. Bioenergy production requires land, so bioenergy consumption is a possible driver for deforestation. Therefore forest area as proportion of total land area is included as indicator.

Agricultural land area

Deforestation can be caused by different drivers, so to check that the effect is attributable to agriculture for bioenergy the agricultural land area as proportion of total land area is also included as indicator.

Bioenergy production yield

In addition to the level of bioenergy production, land use efficiency determines the total land requirement for bioenergy production. Indicators for this are included by the GBEP but not by the UN as they are too specific for bioenergy. Yields are a key value in bioenergy research, so with this the results of IMAGE can be compared to other literature. Additionally annual yield growth rates are included as check of the model behaviour.

Intermediate link

SDG 1 – No poverty

Poverty

The UN proposes three indicators in different formulations related to the number of people living in poverty. In existing literature this is translated to the percentage of population living below the poverty line (income below 1.90 US$/day) (OECD, 2016; Sachs et al., 2016). The Gini coefficient represents welfare inequality within a society. Both the economic growth and Gini coefficient are model input parameters as set by the SSPs. Consequentially, the poverty ratio is defined in the SSP scenarios and is not variable in the IMAGE model. In IMAGE SDG 1 is therefore not affected by bioenergy use and apart from recommendations (section 5.1) further neglected in this research.

SDG 3 – Good health and well-being

The majority (3.1 to 3.8) of targets for SDG 3 are related to (infectious) diseases and healthcare problems. Bioenergy is assumed to have a negligible impact on these, so no indicators for these problems are included. Target 3.9 is aimed at pollution and contamination problems, which bioenergy could impact.

Non-GHG air pollutants

UN indicator 3.9.1 includes mortality from ambient air pollution. The emission of non-GHG air pollutants has also been included by the GBEP as indicator for sustainable bioenergy. Agriculture for production of bioenergy and fuel burning emissions are expected to impact the emissions of non-GHG air pollutants so are therefore included as indicator.

Indoor smoke

Mortality attributable to household air pollution is also included in UN indicator 3.9.1. Indoor smoke from burning solid fuels is the largest contributor to this problem and known to cause many deaths (WHO, 2016). The burning of solid fuels can be affected by bioenergy due to modern energy substitute price changes and solid fuel availability changes. Indoor smoke can thus be affected by bioenergy use and is included as indicator.

SDG 9 – Industry, innovation and infrastructure

GHG emissions per unit added value

To monitor efficiency improvements included in SDG 9 the UN proposes indicator 9.4.1 'CO2 emission per unit of value added'. As this indicator depends on GHG emissions and changes in economic growth it combines environmental and economic effects of bioenergy use. Therefore it provides additional information to the 'GHG emissions per unit energy' indicator for in SDG 7.

Freight

Freight volume is listed by the UN as proposed indicator 9.1.2. The GBEP includes logistics for distribution of bioenergy as indicator. Concerns regarding bioenergy freight are the typically low energy densities of biomass and the possible distances between bioenergy producing and consuming regions. Extensive bioenergy use is thus expected to impact this indicator.

SDG 14 – Life below water

Nutrient pollution

Goal 14.1 aims at reducing marine pollution from among others nutrient pollution. Agriculture is a known contributor of marine nutrient pollution by run-off from nutrients into surface water (Howarth, Sharpley, & Walker, 2002). The agriculture required for bioenergy production is thus related to nutrient pollution, therefore nutrient pollution has been added as indicator.

2.4 Indicator methods

This section elaborates the used method per indicator. While setting up the method per indicator, it became clear they are not equally well developed within IMAGE, therefore they are divided in three tiers. Tier I indicators are well developed in IMAGE, tier II indicators require improvement as they are not directly modelled or modelled with limitations, tier III indicators are not modelled in IMAGE and are added by post-processing with literature data and have a limited scope. The tiers are indicated in the 'Tier' column of Table 4 and Table 5 and this section is presented per tier. To consistently determine the impact of bioenergy use on the indicators, the method per indicator is used for all scenarios (unless noted otherwise in the indicator method below). This results in a maximum of four results per indicator for each SSP (baseline with/without bioenergy and CCM with/without bioenergy). The impact of bioenergy use on each indicator is determined by calculating the difference between the scenario with and without bioenergy (equation 1), where I(j) denotes Indicator number 1 to j.

$$\Delta I_{bioenergy}(j) = I_{scenario\ w.\ bioenergy}(j) - I_{scenario\ w.o.\ bioenergy}(j) \qquad (1)$$

Allowing or preventing bioenergy use is the only model change between scenarios with and without bioenergy, therefore any changes in results can be completely attributed to bioenergy use. The IMAGE model supplies data specified into 26 regions. As this research uses 5 world regions, aggregation of data from 26 to 5 regions is required. For most indicators summation of the data per region into the world regions is possible. In some cases this would lead to incorrect aggregation of the regions (e.g. energy price). For these indicators the used aggregation method is included in the indicator method description below.

Tier I

SDG 3 – Good health and well-being

Non-GHG air pollutants

Total emissions per region of non-GHG air pollutants nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter (PM10) are outputs of the IMAGE model. To account for the differences in toxicology of these substances they have been converted to human toxicity potentials (HTP) of inhalation exposure using the values of Huijbregts et al. (2000). HTP values are 1.2 for NO_x, $3.1*10^{-1}$ for SO_2 and $9.6*10^{-2}$ for PM10.

$$\begin{aligned} &NonGHG\ air\ pollutants\ [HTP/yr] \\ &\quad = Emissions_{NOx}[ton/yr] * HTP_{NOx}[HTP/ton] \\ &\quad + Emissions_{SO2}[ton/yr] * HTP_{SO2}[HTP/ton] \\ &\quad + Emissions_{PM10}[ton/yr] * HTP_{PM10}[HTP/ton] \end{aligned} \tag{2}$$

SDG 7 – Affordable and clean energy

GHG emissions per unit energy

Final secondary energy use and total GHG emissions of the energy supply sector are directly reported in IMAGE. Secondary energy use is selected over primary energy use because it includes changes in conversion efficiencies which may occur with shifting energy sources.

$$GHG\ emissions\ per\ unit\ energy[MtCO_2/EJ] = \frac{Emissions_{Energy\ supply\ sector}\ [Mt\ CO_2/yr]}{Final\ energy\ use\ [EJ/yr]} \tag{3}$$

Share renewable energy

Following the International Energy Agency (IEA), renewable energy sources are defined as biomass, wind, solar, geothermal and hydro (IEA, 2013). Note that traditional biomass use is defined as renewable and nuclear energy is defined as non-renewable. In IMAGE the Total Primary Energy Supply (TPES) and a breakdown of TPES to sources are reported. Biomass and non-biomass renewables (which consists of wind, solar, geothermal and hydro) are two of the reported TPES sources.

$$Share\ renewable\ energy\ [\%] = \frac{Primary\ energy_{Biomass}[EJ/yr]\ +\ Primary\ energy_{non-biomass\ renewable}[EJ/yr]}{TPES\ [EJ/yr]} \tag{4}$$

The share of renewable energy is selected for use as indicator over the more specific share of bioenergy. This is to include possible pushing-out of other renewable energy as side-effect of allowing bioenergy use in the indicator result.

Energy price

Prices of different energy forms and carriers are available in IMAGE. From these the electricity price is selected for use since it is a high-quality form of energy which can be used for many applications and changes in conversion efficiencies by shifting energy sources are included in the price. The electricity price per region is a direct output of IMAGE. Prices are reported in US dollars with inflation correction to 2005 level. As summation of prices per region into the world region is not valid, the average of the region prices weighted to electricity use has been calculated (equation 5).

$$Electricity\ price\ [US\$2005/GJ] = \sum_{regions} Elec.price_{region}[US\$2005/GJ] * \frac{Elec.use_{\ region}[EJ/yr]}{Elec.use_{\ world\ region}[EJ/yr]} \quad (5)$$

Traditional biomass use

Traditional biomass use is a direct output of IMAGE, no post processing other than summation into the world regions is required. Traditional biomass use is reported in EJ/yr.

Energy supply diversity

The GBEP suggest to represent diversity of energy supply with the Herfindahl-Hirschman index (HHI) (GBEP, 2011). Another index for presenting the energy diversity is the Shannon index (Kruyt et al., 2009). For assessing supply concentration the HHI index is almost exclusively used, including use by the IEA (GBEP, 2011; Kruyt et al., 2009). The HHI is therefore selected as index for energy diversity. The HHI index is defined as the summation of the fractions per energy source (equation 6).

$$HHI = \sum_i p_i{}^2 \quad (6)$$

With p_i for fraction per source. A lower HHI indicates a more diverse energy supply. The possible energy supply sources are defined as coal, gas, non-biomass renewables, nuclear, oil, modern biomass and traditional biomass. A cut-off minimum share of 5% has been used, below this the shares have been aggregated into one source. With seven possible sources the theoretical minimum HHI is 0.14 (all sources have an equal share), the maximum HHI is 1 (one source supplies all energy). To obtain world region results, the share per energy source has been calculated by dividing the total world region energy supply of that source over the total world region TPES. With this the need for weighted aggregation of HHI indices per region to world region level is avoided.

SDG 9 – Industry, innovation and infrastructure

GHG emissions per unit value added

The Kyoto GHG emissions as described in indictor 'GHG emissions' for SDG 13 are also used for this indicator. Additionally, IMAGE outputs the Gross Domestic Product (GDP) per region in US dollars with inflation correction to 2005 level. Using this data the GHG emission intensity per value added is calculated (equation 7).

$$GHG\ emission\ intensity\ [kg\ CO_2eq./US\$2005] = \frac{Emissions\ Kyoto\ gasses\ [Mt\ CO_2eq/yr]}{GDP\ [billion\ US\$2005/yr]} \quad (7)$$

SDG 13 – Climate action

Non-renewable energy use

Following the IEA non-renewable energy sources are defined as nuclear, oil, natural gas and coal (IEA, 2013). In IMAGE a breakdown of primary energy supply by sources is reported, the non-renewable sources are summed.

$$\begin{aligned}Non-renewable\ energy\ consumption\ [EJ/yr] \\ = Primary\ energy_{coal}[EJ/yr] + Primary\ energy_{natural\ gas}[EJ/yr] \\ + Primary\ energy_{oil}[EJ/yr] + Primary\ energy_{nuclear}[EJ/yr]\end{aligned} \quad (8)$$

GHG emissions

Reported by IMAGE are annual CO_2 equivalent emissions of Kyoto gasses per region. The Kyoto gasses cover the six main greenhouse gasses (CO_2, CH_4, N_2O, HFCs, PFCs and SF6) (UNFCCC, 2008). These gasses are converted to the global warming potential (GWP) of CO_2 with a 100-year lifetime using the values in IPCC (2007) (e.g. $GWP_{ch4} = 25$). Next to summation into world regions no other operations are required.

Energy related emissions per capita

The total CO_2-equivalent emissions of the energy supply sector is an output of the IMAGE model. This includes emissions from production of energy, transport and conversion emissions and final use emissions but excludes land use change emissions. As population sizes are defined in the SSP scenarios they are independent of bioenergy use. Indicator changes are thus driven by energy supply emission changes only, but are still presented per capita to allow comparison between regions of different sizes.

$$Energy\ emissions/capita\ [t\ CO_2eq/person * year] = \frac{Emissions_{energy\ supply\ sector}\ [Mt\ CO_2eq/yr]}{Population\ [million\ people]} \quad (9)$$

SDG 15 – Life on land

Forest area

Within the IMAGE model the total land cover use is calculated on a 0.5x0.5-degree grid and broken down to forest, cropland, pasture, other land, other natural land and built-up area. With this the forest area is calculated.

$$Forest\ area\ [\%] = \frac{Forest\ area\ [million\ km^2]}{Total\ land\ cover\ [million\ km^2]} * 100\% \quad (10)$$

Agricultural land area

To calculate the agricultural land area the same method as the forest area indicator is used. Agricultural land is defined as cropland (including energy crops), pastures and other cultivated land.

$$Agricultual\ land\ area\ [\%] = \frac{Land\ cover_{Cropland+pasture+other\ arable\ land}\ [million\ km^2]}{Total\ land\ cover_{total}\ [million\ km^2]} * 100\% \quad (11)$$

Tier II

SDG 2 – Zero hunger

Food price

The price index of non-energy crops and livestock reported per region is available in IMAGE. The aggregation of regions into world region is weighted to population, as this reflects how many persons are affected by the price changes. Baseline for the index are 2005 price levels.

$$Food\ price_{world\ region}[index] = \sum_{regions} Food\ price_{region}[index] * \frac{Population_{region}[million]}{\sum_{world\ region} population\ [million]} \qquad (12)$$

Cereal yield

Output of the model is cereal production per region and land cover in use for cereal production. Cereals are defined as the aggregate of wheat, rice, maize, corn, millet, sorghum, barley, oats and rye. This data is first summed into the world regions and then used for calculation of the average cereal yield per world region. By summing first and calculating the yield secondly, the need for weighted aggregation is avoided.

$$Cereal\ yield\ [t\ dm/ha/yr] = \frac{Cereal\ production\ [million\ t\ dm/yr]}{Land\ cover_{cropland\ for\ cereals}\ [million\ ha]} \qquad (13)$$

SDG 3 – Good health and well-being

Indoor smoke

In IMAGE the mortality attributable to indoor smoke is not directly available. Indirect methods to derive this such as in Desai et al. (2004) require as input data the number of people exposed to indoor smoke and the burden of disease. The burden of disease is dependent on factors such as pollution levels, duration of exposure (i.e. time spent in the smoke) and demographics of the exposed population (age, gender). Bioenergy is assumed not to affect these factors making the burden of disease independent of bioenergy use. Mortality attributable to indoor smoke is in this case linearly related to the number of people exposed to indoor smoke. Available in IMAGE is the percentage of population using solid fuels, assumed is that people using solid fuels are also exposed to indoor smoke. Converting the relative data into absolute data on region level enables aggregation into the world regions.

$$Pop.exposed\ to\ indoor\ smoke\ [million] = pop.using\ solid\ fuels[\%] * population\ [million] \qquad (14)$$

SDG 9 – Industry, innovation and infrastructure

Freight

Freight volumes are reported by IMAGE per region in billion ton*km/year. Other than summation into the world regions no other operations are required. Despite the availability of data, freight is classified as a tier II indicator since freight demand is price driven only. This is further discussed in section 4.1.

Tier III

SDG 6 – Clean water and sanitation

Water footprint

The water footprint (WF) of bioenergy use is not calculated in IMAGE, so instead it is calculated outside of IMAGE by combining available data outputs with literature data. Only the WF of bioenergy crop cultivation is assessed. Bioenergy from residues are considered a by-product, so all water use is allocated to the main product. Traditional biomass is assumed to be extracted from natural lands and forests, for which the water use is unaffected by the biomass extraction so no water use is accounted to this. It is projected that first-generation bioenergy crops (e.g. corn, rapeseed, sugarcane) are phased out by 2030 and will be replaced by second generation lignocellulosic crops (e.g. Miscanthus, switchgrass, short rotation coppice (SRC) poplar).

Compared to the WF of energy supply production the WF of operation is orders of magnitudes lower for bioenergy and is therefore excluded (Mekonnen, Gerbens-Leenes, & Hoekstra, 2015). In water footprint research a distinction is used between blue water (ground- and surface water), green water (precipitation) and grey water (process water use) (Gerbens-Leenes, Hoekstra, & van der Meer, 2009b). Grey water use is considered negligible for bioenergy production. Bioenergy crop cultivation is assumed to be non-irrigated as the economic value of bioenergy production is too low to justify the costs. This is in line with the model output of irrigated land area used for bioenergy production which is zero for all scenarios and years. This means that the water footprint consists of green water use only. The majority of this is the evapotranspiration (evaporation due to solar irradiation and transpiration by the crops), which is assumed to be independent of bioenergy yields (Borek, Faber, & Kozyra, 2010). As result of this assumption, the water footprint per unit energy decreases with yield improvements. This effect is accounted for by a yield improvement factor, defined as the actual yield over the baseline yield. An overview of water intensity values as found in literature are in Table 6. The average literature water intensity is used as baseline data for 2010.

Table 6 – Literature values of bioenergy crop production water intensity

Source	Area	Crop type	Value [m³/GJ]
Borek et al. (2010)	Poland	Miscanthus	7.0-9.4
Borek et al. (2010)	Poland	SRC willow	11.5-13.0
Gerbens-Leenes et al. (2009b)	NL/US/Brazil/Zimbabwe	Miscanthus	20/37/49/64
Gerbens-Leenes et al. (2009b)	NL/US/Brazil/Zimbabwe	SRC Poplar	22/42/55/72
Clarens et al. (2010)	US	Switchgrass	18
Average (equal weights)			32.3

The IMAGE projected biomass production, the baseline water intensity (Table 6) and the yield improvement factor are combined into equation 15 for calculation of the WF for bioenergy.

$$\begin{aligned} WF\ biomass_{energy\ crops,\ \ year}[km^3/yr] = \\ Primary\ energy_{biomass,\ \ energy\ crops}[EJ/yr] \\ * Water\ intensity_{energy\ crops,\ \ 2010}[km^3/EJ] \\ * \frac{Yield_{enegy\ crops,\ \ 2010}[EJ/km^2]}{Yield_{energy\ crops,\ \ year}[EJ/km^2]} \end{aligned} \qquad (15)$$

SDG 8 – Decent work and economic growth

Employment

Within the IMAGE model no data is available on (un)employment, instead this is calculated outside IMAGE. As with the WF, only the direct employment effects of bioenergy crop cultivation are assessed.

Labour requirements for bioenergy crop cultivation as described in literature are used, again assuming by 2030 all bioenergy will be supplied by second generation lignocellulosic crops. Also in line with earlier assumption of residues being a by-product, labour for bioenergy from residues is allocated to the main product. Bioenergy production labour requirement data in full-time equivalent (FTE) jobs as found in literature are in Table 7. Only labour requirements for normal operation of bioenergy cropland is assessed, labour requirements for creating bioenergy cropland are excluded.

Table 7 – Literature values of bioenergy crop production employment

Source	Area	Crop type	Value [FTE/ha/yr]
Thornley et al. (2008)	Unspecified	Miscanthus	0.0014
Thornley et al. (2008)	Unspecified	SRC poplar	0.001
De la Rúa & Lechón (2016)	France	Miscanthus	0.018
Singh & Fehrs (2001)	US	Switchgrass	0.0041
Singh & Fehrs (2001)	US	SRC Poplar	0.0049
Singh & Fehrs (2001)	US	SRC Willow	0.0010
		Average (equal weights)	**0.0051**

The data in Table 7 is directly extracted for Thornley et al. (2008). De la Rúa & Lechón (2016) use an Input-Output (IO) model for employment effects, in which 91 FTE is required for exploitation of 400 ha. Of this 24 FTE is agricultural and 30% is direct employment, for consistency with the other sources only this part is included. The results in Singh & Fehrs (2001) are reported in FTE for electricity production, additionally to this a conversion efficiency of 30% (biomass co-firing in coal power plant) and yields of 330, 380 and 140 GJ/ha/yr for switchgrass, poplar and willow (Twidell & Weir, 2015) are used.

The labour requirement per hectare is used independent of yields as the number of operations (e.g. sowing, fertilizer application) is assumed to be constant. With this data and assumptions equation (16) is used to calculate the employment in bioenergy crop cultivation.

$$\begin{gathered} Employment\ [FTE/yr] = \\ Average\ labour\ requirement_{bioenergy\ crop\ cultivation}[FTE/ha/yr] \\ *\ Land\ cover_{cropland,\ \ energy\ crops}[ha] \end{gathered} \qquad (16)$$

SDG 13 – Climate action

Land use GHG emissions

The benefits (carbon uptake during growth) and burdens (land-use change emissions) of bioenergy use are not occurring simultaneously. Emissions tend to occur early in the bioenergy use phase and are high when natural land is converted to agricultural land, while uptake rates by biomass growth are lower but occur as long as the land is in use for biomass growth. The timespan for which land use emissions are assessed thus influences the results. Bioenergy production is assumed to continue after the time horizon of this study (based on data from the same scenarios until 2100), therefore three timespans are assessed: 2010 to 2030, 2010 to 2040 and 2010 to 2050. For the timespans up to 2040 and 2050, developments after 2030 are also included with this method. In other words, the land use GHG emissions and bioenergy production levels are not kept constant on 2030 levels after 2030.

As yearly data is required for calculations over the timespans while IMAGE outputs data with an interval of ten years, linear interpolation has been applied between these points. Land use emissions of CO_2, CH_4 and SO_2 for five land categories (forest, cropland, grassland, settlement, other land) are reported by the IMAGE model. This includes emissions and removals by change in land use type, biomass (forest) clearings, soil organic carbon change and potential uptake changes by biomass growth. Emissions from final use of bioenergy and fertilizer use are excluded from these emissions. In line with earlier methods all land use emissions are converted to GWP equivalents of CO_2 with a 100-year time horizon using the values of the IPCC (2007) ($GWP_{CH4} = 25$, $GWP_{N2O} = 298$).

The cumulative bioenergy crop production and cumulative land use emissions due to bioenergy crop cultivation for each IMAGE interval were calculated first (equation 17 and equation 18), next these are used to derive land use emissions per unit energy over the timespan (equation 19).

$$\begin{aligned} Cum.\,emissions_{land\ use,\ bioenergy,\ interval}[Mt\ CO_2eq] &= interval\ length\ [yr] \\ &* \left(\frac{1}{2}\sum_{regions}(land\ use\ emissions_{w.\ bioenergy,interval\ start}\right. \\ &+ land\ use\ emissions_{w.\ bioenergy,interval\ end})[Mt\ CO_2eq/yr] \\ &- \frac{1}{2}\sum_{regions}(Land\ use\ emissions_{w.o.\ bioenergy,interval\ start} \\ &\left.+ Land\ use\ emissions_{w.o.\ bioenergy,interval\ end})\ [Mt\ CO_2eq/yr]\right) \end{aligned} \tag{17}$$

$$\begin{aligned} Cum.\,primary\ energy_{energy\ crops,\ interval}[EJ] &= interval\ length\ [yr] \\ &* \left(\frac{1}{2}\sum_{regions}(Primary\ energy_{energy\ crops,\ w\ .bioenergy,interval\ start}\right. \\ &+ Primary\ energy_{energy\ crops,\ w\ .bioenergy,interval\ end})[EJ/yr] \\ &- \frac{1}{2}\sum_{regions}(Primary\ energy_{energy\ crops,w.o.bioenergy,interval\ start} \\ &\left.+ Primary\ energy_{energy\ crops,w.o.bioenergy,interval\ end})[EJ/yr]\right) \end{aligned} \tag{18}$$

$$Land\ use\ emissions_{energy\ crops}[Mt\ CO_2eq/EJ] = \frac{\sum_{intervals} Cum.\,emissions_{land\ use,\ bioenergy,\ period}[Mt\ CO_2eq]}{\sum_{intervals} Cum.\,primary\ energy_{energy\ crops,\ period}[EJ]} \tag{19}$$

SDG 14 – Life below water

Nutrient pollution

Nutrient emissions to water are not available in IMAGE and, as with the water footprint and employment, calculated for bioenergy post-model. In line with earlier methods, bioenergy is assumed to be produced by second generation energy crops. Literature values of eutrophication in PO_4 equivalents for bioenergy cultivation are in Table 8.

Table 8 – Literature values of bioenergy crop production eutrophication potential

Source	**Area**	**Crop type**	**Value [gr PO_4eq/GJ]**
Clarens et al. (2010)	US	Switchgrass	19.2
Gabrielle et al. (2013)	France	SRC Eucalyptus	50
Gasol et al. (2009)	Italy	SRC Poplar	3.4
Djomo, Kasmioui, & Ceulemans (2011)	Europe	SRC Willow	94
Monti, Fazio, & Venturi (2009)	-	Miscanthus and switchgrass	4 - 20
		Average (equal weights)	29.8

As crop type is unknown in 2030 the average value has been used. The eutrophication potential per unit energy is kept constant over time. Equation 20 is used to calculate the final eutrophication potential of bioenergy crop production.

$$\begin{aligned} Eutrophication[M\ kg\ PO_4eq/yr] \\ = Eutrophication_{energy\ crops}[gr\ PO_4eq/GJ] \\ * Primary\ energy_{\ biomass,\ \ energy\ crops}[EJ/yr] \end{aligned} \quad (20)$$

SDG 15 – Life on land

Bioenergy production yield

The IMAGE model outputs the land area in use for bioenergy crop cultivation and primary energy supplied by bioenergy crops. With these outputs the annual bioenergy production yield is calculated with equation (21).

$$Bioenergy\ prod.yield\ [GJ/ha * yr] = \frac{Primary\ energy_{\ biomass,\ \ energy\ crops}[GJ/yr]}{Land\ cover_{cropland,\ \ energy\ crops}[ha]} \quad (21)$$

As check for model behaviour the year-on-year yield growth rate is calculated. The rate has been assumed constant within the model periods, resulting in non-linear yield increase. It is calculated using equation (22).

$$Yield\ growth\ rate\ [\%] = (\left(\frac{Yield_{interval\ end}}{Yield_{interval\ start}}\right)^{\frac{1}{interval\ length}} - 1) * 100\% \quad (22)$$

2.5 Aggregation indicators per SDG

With several SDGs represented by multiple indicators, a method to aggregate indicators into a single SDG result is required. Before setting up the method current literature is reviewed for the used method and described in Box 3. This research and existing literature differ with respect to the level of detail: in existing literature the SDGs are assessed on a national level while this research assesses on world region level. With a much smaller dataset the practice of removing outliers would remove a relatively large part and is therefore not used.

As result of the different level of implementation in IMAGE, tier I and tier II indicators are handled differently compared to tier III indicators. Tier I and tier II indicators are implemented in IMAGE, so the indicators are affected by developments of all parts of society included in the model. Exception to this is the land use GHG emissions indicator, which lacks a counterfactual and is handled as a tier III indicator. Tier III indicators are calculated post-model for the bioenergy sector exclusively. With this practice, first the indirect effects of bioenergy on other parts of society are neglected. Secondly, for the scenarios without bioenergy the absolute indicator results covers not all parts of society. Because of this lack of counterfactual, for tier III indicators no bioenergy induced relative change can be given. Due to this scope difference and inaccuracy of results, tier III indicators are excluded from use in the SDG results. With this practice for SDG 6, 8 and 14 there are no suitable indicators for a SDG result and instead they are only qualitatively assessed in the discussion section.

Shown in Table 4 and Table 5 in the column 'Pos. dev.' is the desired direction of move for each indicator. Marked with a minus sign are indicators for which a decrease is deemed a positive development (i.e. lower is better), marked with a plus sign are indicators for which an increase is deemed a positive development (i.e. higher is better).

The normative proposal of the UN that all indicators are equal (United Nations, 2015b) is used in this research, so the weight of each indicator per SDG is inversely depended on the number of indicators per SDG. With this assumption the formula used to aggregate the results is given by equation 23.

$$\Delta I_{SDG,\ bioenergy} = \frac{1}{N}\sum_{j=1}^{N} \Delta I_{bioenergy}(j) * direction(j) \qquad (23)$$

With ΔI for Indicator change between the scenarios with and without bioenergy (equation 1), N indicators per SDG and the positive development operator noted by direction(j). With the used convention on direction of movement, positive SDG indicator results represent improvements and negative results represent worsening.

Equal weights for all indicators per SDG are used as it corresponds best with the UN intention of 'equal importance with other goals and targets' (United Nations, 2015b) and since it is also used in existing research that monitors SDG progress. Furthermore, it is the most intuitive method to assess and compare indicators. Lastly it is the least subjective indicator weighting judgement, which minimizes the influence of the choice on the results.

United Nations

The UN proposes targets and indicators for each SDG, however currently they do not propose a method to aggregate these indicators. Instead the stated means of implementation is with equal importance of each goal and target with the other goals and targets (United Nations, 2015b). With this the UN refrains from all value judgement to the importance of individual indicators and goals.

Sachs et al.

The operational SDG research of Sachs et al. (2016) acknowledges the equal importance of each indicator as put forward by the UN and incorporated this in their method. The method used further consists of rescaling each individual indicator to prevent the effect of low outliers by removing the 10% lowest scores after which arithmetic mean of the indicators is used to aggregate results per SDG (Sachs et al., 2016). The arithmetic mean is selected over the geometric mean and Leontief production for reasons of substitutability of indicators and ease of communication (Sachs et al., 2016).

OECD

The research to the SDG progress by OECD (2016) uses an aggregation method similar to Sachs et al. First the 10% lowest scores are disregarded to remove outliers and secondly the indicators per SDG are averaged using equal weights.

Box 3 – Aggregation methods in literature

2.6 Defining synergies and trade-offs

Formulated in the research question are trade-offs and synergies between the sustainable development goals and bioenergy use. With the inclusion of a desired direction of move for each indicator in the method for aggregation into a single SDG result, trade-offs and synergies are defined. For SDGs with a net positive result bioenergy use is in synergy with the SDG goal, for SDGs with a net negative result bioenergy use is a trade-off with the SDG goal.

3 Results

In section 3.1 the results for each individual indicator is presented and discussed. In section 3.2 the results of the composite SDG indicators are presented and discussed. All the results presented in this section show the difference between the cases with and without biomass, i.e. for the individual indicators the results of equation 1 are presented and for the composite SDG indicators the results of equation 23 are presented. All data presented is for 2030, in line with the temporal scope set in the research question.

To help contextualise the role of bioenergy, shown in Figure 4 is an overview of the total primary energy supply broken down to several sources for the scenarios with bioenergy use. Table 9 lists the land use for energy crop cultivation for the scenarios with bioenergy use.

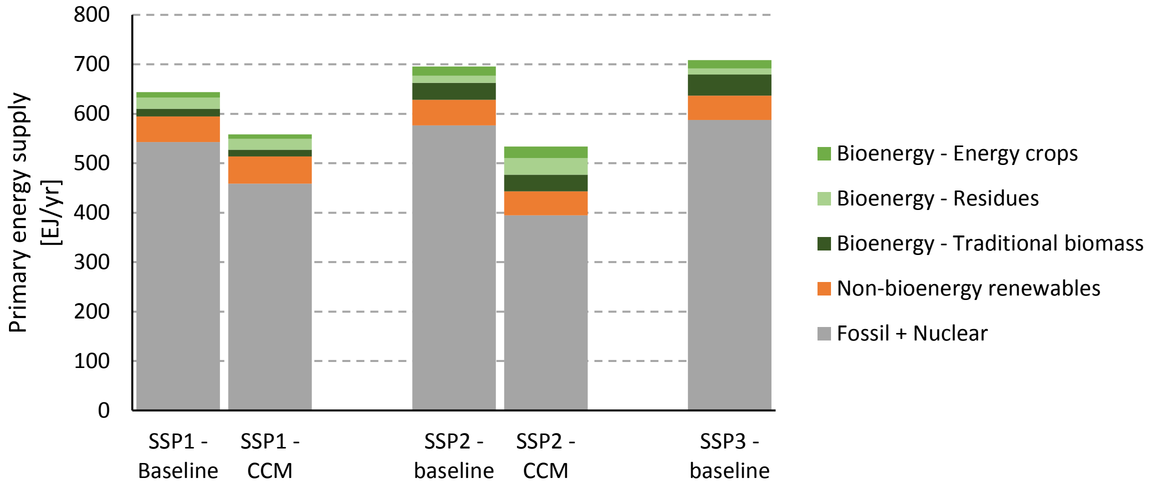

Figure 4 – Global primary energy supply per scenario

Table 9 – Global land use for energy crop cultivation per scenario

	Baseline	**CCM**
	Unit: million hectares	
SSP1	18.17	13.88
SSP2	29.37	34.80
SSP3	24.84	-

3.1 Indicator results

A selection of interesting indicators and/or results is included in this section. Depending on the indicator the most relevant results are shown in a graph or table for different SSPs, regions, scenarios or a combination. All results per region on indicator level are included in Appendix A - Indicator results.

Generally, under the scenario storyline of SSP1 the energy use and baseline emission are lower compared to SSP2, especially in the CCM cases. The effect of bioenergy (presented below) is therefore less pronounced.

Tier I

SDG 3 – Good health and well-being

Non-GHG air pollutants

Total emissions of non-GHG air pollutants are almost unaffected (global changes less than 0.3% for SSP1 and SSP2, 2% for SSP3) by bioenergy use. Regional differences do occur but also these are very small, indicating that bioenergy production processes are clean and emit low amounts of pollutants. The reduction of non-GHG emissions due to implementation of a CCM policy in SSP1 and SSP2 is magnitudes greater compared to the reduction by bioenergy use.

SDG 7 – Affordable and clean energy

GHG emissions per unit energy

Emissions per unit energy (Figure 5) decline only little (around 1%) for all scenarios except SSP2 with CCM (decline of 13%). When tracing the precedent data, it is observed that the final energy use is stable regardless of bioenergy use and changes are driven by emission changes in the energy supply sector.

For the baseline scenarios the low impact of bioenergy is as without an emission tax, by 2030 the competitiveness of bioenergy is limited with respect to other energy sources. For the scenarios with CCM policy bioenergy is more competitive and impacting the emissions, however this effect is strongest after 2030. Only in SSP2 with CCM the effect occurs early enough to significantly lower emissions per unit energy.

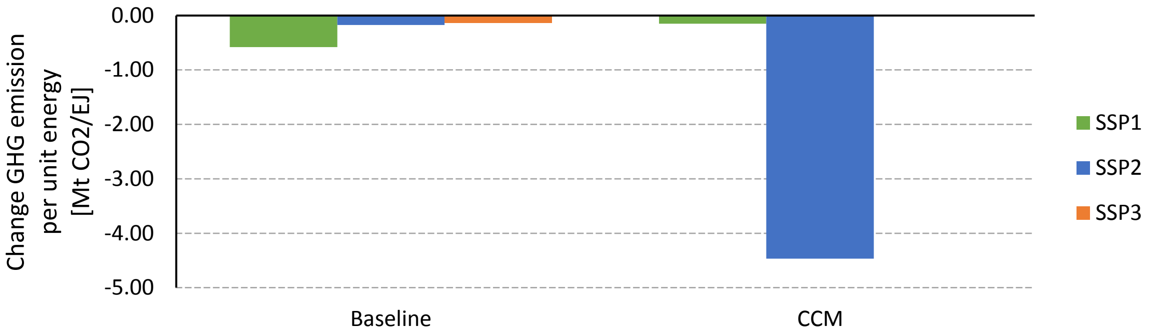

Figure 5 – Change in GHG emissions per unit energy by bioenergy (world)

Share renewable energy

As shown in Figure 6, for all scenarios the share of renewables increases. In the baseline scenarios, bioenergy is less competitive due to the absence of a carbon price. This results in low increases of the renewables share. In the CCM scenarios a carbon price is included, so higher increases of the renewables share are expected. The low increase in SSP1 CCM is, as with the GHG emissions per unit energy, result of the timeframe. In the SSP1 CCM scenario renewables are used on large scale after 2030. In the SSP2 CCM scenario large scale introduction of renewables is before 2030, resulting in a high increase of the share of renewables in the energy supply.

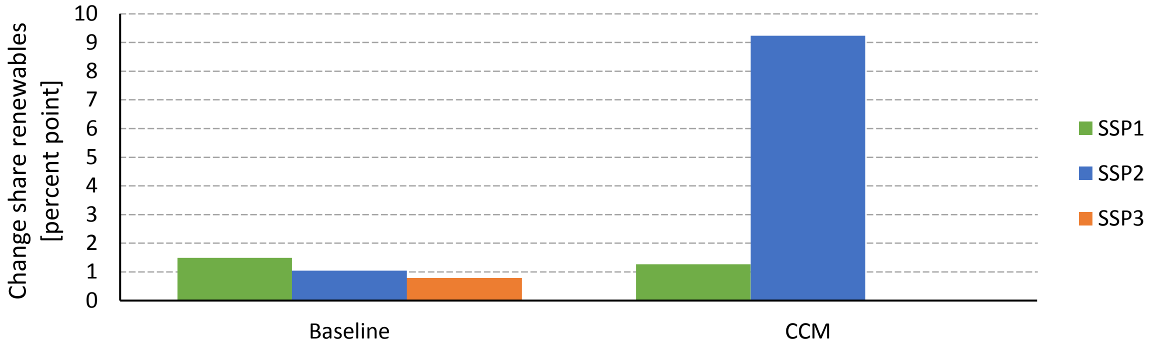

Figure 6 –Change in share renewables by bioenergy (World)

Energy price

In all scenarios, allowing bioenergy to be part of the energy system lowers the energy price (Figure 7). This is in line with the expectation that bioenergy lowers prices as it increases competition, although the impact is limited with a maximum price decrease of 3% for SSP2 with CCM.

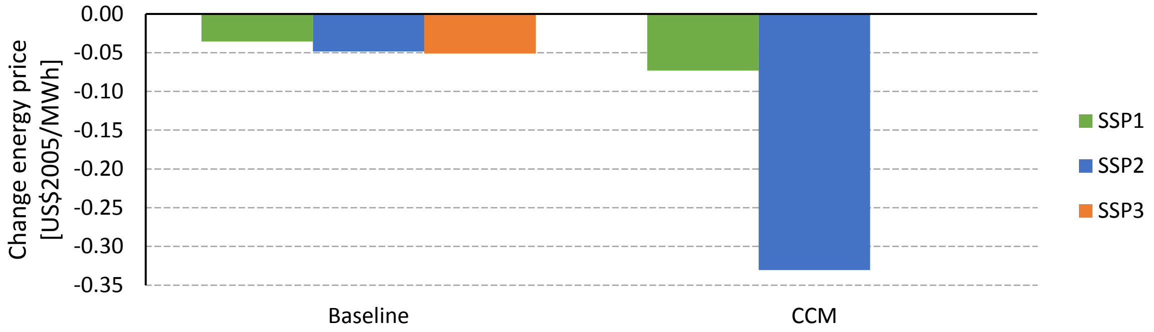

Figure 7 – Change in energy price by bioenergy (World)

Price developments are similar for all regions (Appendix A table A8), which is due to the assumption in IMAGE that the energy trade market operates globally and is open. In the CCM scenarios the energy price decreases strongest. This is in line with expectations since the CCM policy puts constraints on the carbon emissions and thus limits the number of applicable sources. Bioenergy can therefore have a bigger impact compared to the baseline scenarios.

Traditional biomass use

Traditional biomass use declines in all scenarios (Figure 8). Within the IMAGE model, traditional biomass can be used for space heating and cooking. After demand of energy for these functions is set the choice of fuel type to fulfill the demand is determined on the base of relative energy supply costs (Stehfest et al., 2014, p. 81). With introduction of bioenergy the costs of modern energy shift closer to the costs of traditional bioenergy. As result a lower share of the energy demand is fulfilled with bioenergy. Compared to the energy price results (Figure 7) the trend is different, as relative changes are shown here. Under the scenario storylines, the absolute traditional biomass use is lower in SSP1 than SSP2. While the absolute changes are closer (Appendix A table A9), they result in higher relative changes for SSP1.

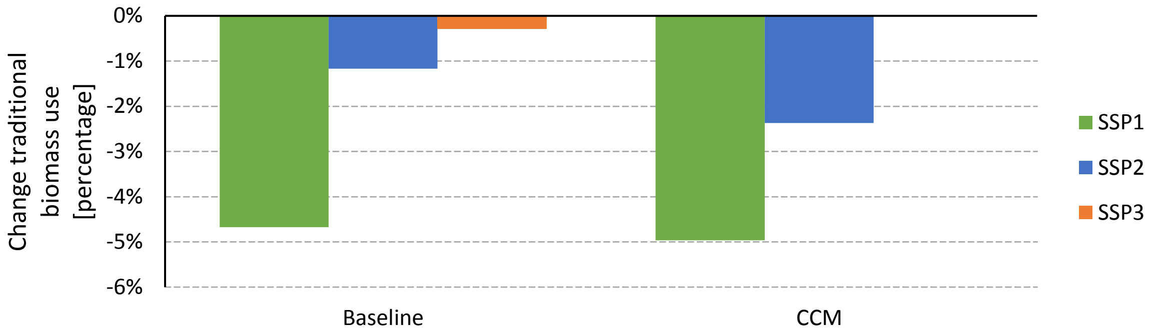

Figure 8 – Relative change in traditional biomass use by bioenergy (World)

Energy supply diversity

The trend of changes in energy supply diversity are in line with the share of renewable energy. This is logical as renewables are defined as a separate energy source, so an increase of the share of renewables induces an increase in energy supply diversity.

SDG 9 – Industry, innovation and infrastructure

GHG emissions per unit added value

GHG emission per unit GDP (Figure 9) trends are comparable to GHG emissions (Figure 11). This is explained by the used method and model, in which economic developments are a driver specified within the SSP scenarios. Consequentially, economic developments are unaffected by bioenergy use and the emission intensity changes are driven by GHG emissions alone.

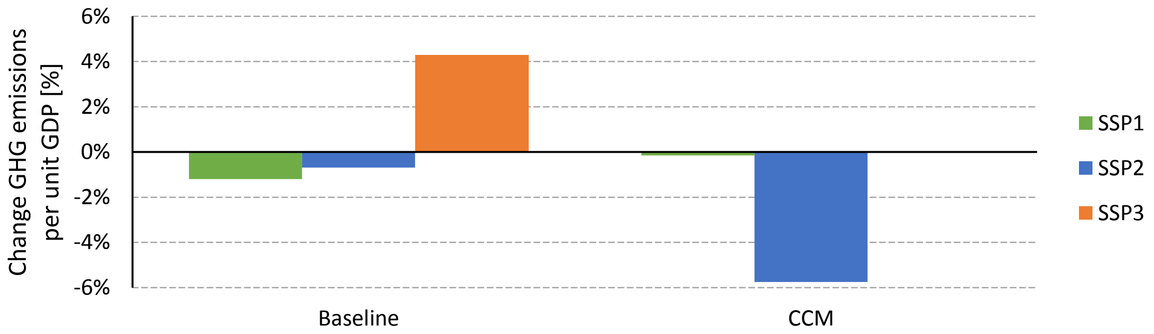

Figure 9 – Relative change in GHG emission per unit GDP by bioenergy (World)

SDG 13 – Climate action

Non-renewable energy use

With bioenergy use allowed, the energy supplied by non-renewable sources declines in all scenarios (Figure 10). The change is driven by declining fossil energy use, while nuclear energy use is unaffected by bioenergy. Fossil energy use for liquid fuels is responsible for most the decrease, followed by fossil energy use for electricity.

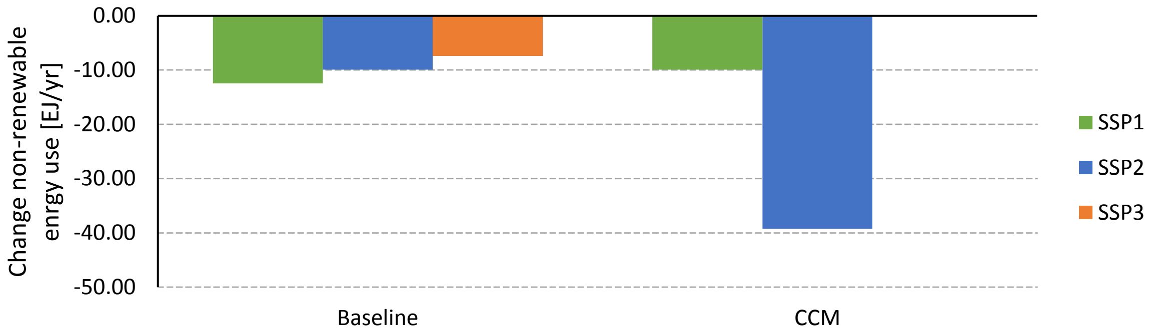

Figure 10 - Change in non-renewable energy use by bioenergy (World)

GHG emissions

Total greenhouse gas emissions changes are positive or negative depending on the scenario (Figure 11). In the baseline, emissions in the SSP1 and SSP2 scenarios decrease slightly, but increase for SSP3. In the CCM scenarios, changes in SSP1 are so small it is not visible in the graph but emissions decrease significantly under SSP2.

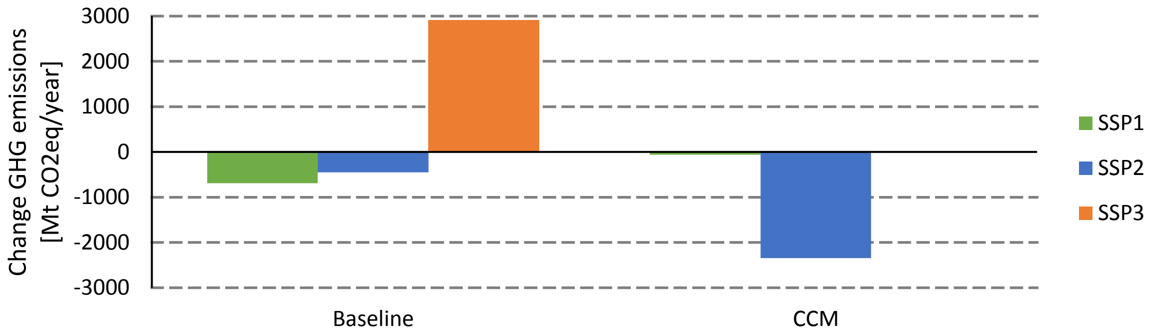

Figure 11 – Change in greenhouse gas emissions by bioenergy (World)

The total GHG emissions follow a different trend compared to the GHG emissions per unit energy (Figure 5) as result of accounting different emissions sources. Here, all emission sources (e.g. land use change emissions) are included, opposed to a limit to direct emissions only in the emissions per unit energy. This explains the increase of emissions in SSP3 baseline scenario, as it is due to increasing land use emissions (discussed in the tier III land use GHG emissions indicator below). These emissions occur as result of conversion of natural land to agricultural land, also shown by the indicators of SDG 15. In the GHG emissions per unit energy indicator (Figure 5) the emissions decrease as the land use emissions are excluded. Furthermore, it is important to note that the used time horizon (2030) limits cover of the bioenergy use effects. As argued later in the discussion of results and methods (section 4), bioenergy has a long payback period for land use change emissions which is not completely covered by the 2030 horizon.

Energy related emissions per capita

Energy related emissions per capita follow almost the same trend as the emissions per unit energy. The indicators are depending on the variables energy supply emissions combined with population size and final energy use respectively. Energy supply sector emissions are used in both indicators so changes affect both indicators. As population size is defined in the SSP scenarios (unaffected by bioenergy use) the conclusion is that final energy use is unaffected by bioenergy.

SDG 15 – Life on land

Forest area & agricultural land area

In all scenarios the forest area lost is almost exclusively to create agricultural land area (Table 10). In case of SSP1 and SSP2 the demand for extra agricultural area is low (below 0.1% of total agricultural area), which is an effect of the storyline assumptions of high yield improvements so abandoned agricultural land can be used for bioenergy production. It is notable that even for SSP2 with CCM (the scenario with the highest bioenergy consumption) this is the case. Under the SSP3 storyline assumptions the yield growth is lower and IMAGE models no surplus agricultural land is available for bioenergy production so instead natural land is converted.

In SSP1, the introduction of CCM results in lower loss of forest compared to baseline. In SSP2 the contrary effect occurs, with introduction of CCM resulting in higher loss of forest. This effect is a combination of decreasing energy use and shift in energy supply under a CCM policy. When checking with Figure 4 and Table 9, the effect of lower energy use in SSP1 CCM results in lower bioenergy consumption. In SSP2 also a reduction of energy use occurs, but accompanied with an increase of bioenergy use.

Table 10 – Change in forest and agricultural land by bioenergy (world)

	Baseline		CCM	
	Unit: million hectares (percentage)			
	Forest	Agricultural land	Forest	Agricultural land
SSP1	-2.20 (-0.06%)	2.25 (0.03%)	-1.05 (-0.03%)	1.13 (0.02%)
SSP2	-1.05 (-0.03%)	1.19 (0.02%)	-2.58 (-0.07%)	2.65 (0.03%)
SSP3	-137.19 (-3.84%)	139.44 (1.81%)	-	-

Tier II

SDG 2 – Zero hunger

Cereal yield & Food prices

The IMAGE model uses a food-first principle with respect to bioenergy. Therefore the current indicator results are not relevant as they are unaffected by bioenergy use (SSP1 and SSP2 results).

SDG 3 – Good health and well-being

Indoor smoke

Bioenergy use has hardly an impact on the number of persons using solid fuels (changes for all regions, under all scenarios below 1%). In the IMAGE model changes in type of used fuel are driven by energy price changes, as with lower energy prices more people can afford modern energy sources. With the observed limited impact of bioenergy to energy prices (indicator result in SDG 7), the limited impact on solid fuel use is in line with this.

The changes in population depending on solid fuels changes less compared to the traditional bioenergy consumption indicator used in SDG 7. Under the assumption that the persons who use traditional biomass the consumption does not change, the results imply a switch from traditional biomass to modern solid fuels for a part of the population using solid fuels.

SDG 9 – Industry, innovation and infrastructure

Freight

Freight levels (Figure 12) are affected only to small extent by bioenergy (max. of 3% global increase in SSP2 CCM). With the freight demand in IMAGE being driven by energy prices alone (section 4.1) and the observed low impact of bioenergy on energy prices (Figure 7) the results are as expected. The dependency of freight demand on energy prices is also reflected on the trend between the scenarios, which is similar for both indicators.

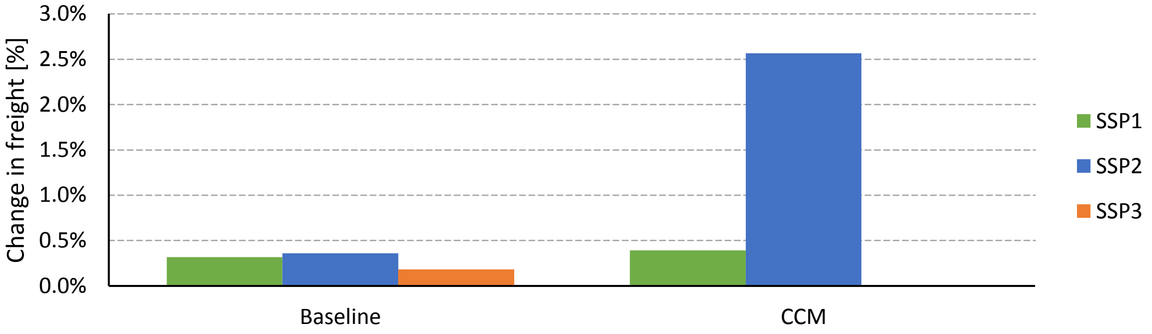

Figure 12 – Change in freight by bioenergy (World)

Tier III

SDG 6 – Clean water and sanitation

Water footprint

The water footprint (Figure 13) is depending on bioenergy crop production and yields. As bioenergy crop production levels differ significantly per region, there is also a large difference between regions for the water footprint (Appendix A – table A5). As IMAGE models the most bioenergy to be produced in Africa and the Middle East (in this thesis combined into one region), consequentially most of the water footprint is in that region. The bioenergy water footprint is compared to literature data in the discussion (section 4.1) to provide context for these results.

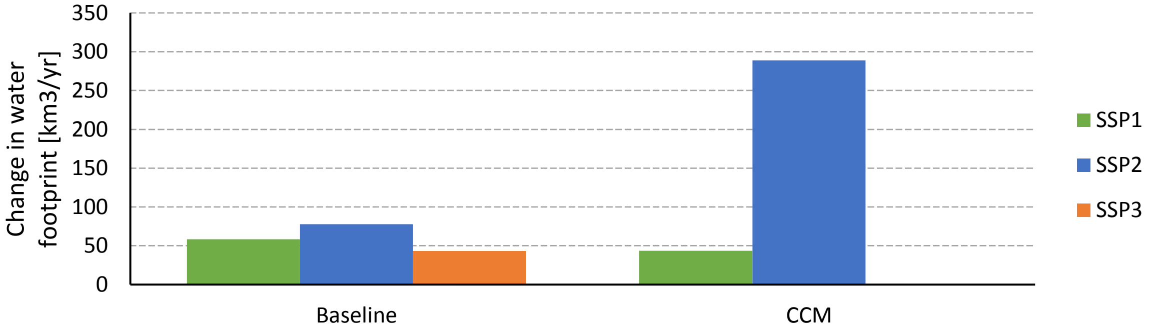

Figure 13 – Change in water footprint of modern bioenergy (World)

SDG 8 – Decent work and economic growth

Employment

As result of the used method, the employment in bioenergy production (Figure 14) is proportional to the bioenergy crop land area. As result, there are also large regional differences in employment (Appendix A – table A11). For all scenarios an increase in employment is projected, however this is partially because potential negative effects of bioenergy production are excluded from the used method. Section 4.1 discusses the validity of these results.

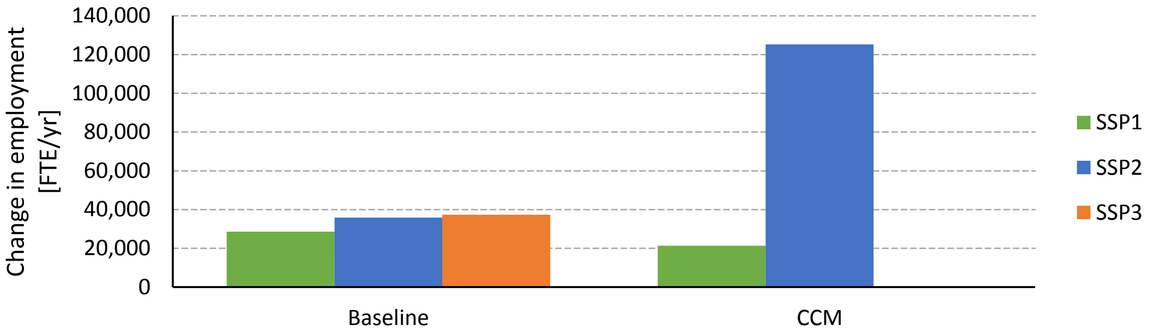

Figure 14 – Change in bioenergy cultivation employment (World)

SDG 13 – Climate action

Land use GHG emissions

The effect of the timeframe selection as pointed out in the method section is strongly present in the results (Table 11). For all scenarios, assessing a longer timeframe reduces the land use emissions per unit energy. The largest decrease is with extension of the timeframe from 2010-2030 to 2010-2040, which implies that most land use change emissions occur relatively short before 2030 (in that case little of the advantages of bioenergy are included, but most of the burdens are).
Land use GHG emissions are lowest for SSP1, as under this SSP storyline bioenergy is mostly produced on abandoned food/feed agricultural lands which have low emission factors (Daioglou, 2016). In SSP2 bioenergy is produced on abandoned food/feed agricultural land and converted natural grassland (Daioglou, 2016). Even if areas with high carbon stocks are protected, conversion of natural grasslands still result in increased land use emissions (Table 11). Under the SSP3 scenario high carbon stock lands are also converted for bioenergy production (Daioglou, 2016), resulting in high emission factors (Table 11).

Table 11 – Change in land use GHG emissions per unit produced bioenergy (world)

	Baseline			**CCM**		
	Unit: Mt CO2/EJ					
	2010-2030	2010-2040	2010-2050	2010-2030	2010-2040	2010-2050
SSP1	119	64	41	189	83	40
SSP2	95	50	40	109	64	50
SSP3	1642	607	232	-	-	-

SDG 14 – Life below water

Nutrient pollution

With the used method, eutrophication levels (Figure 15) are directly related to bioenergy production levels. The results thus also differ strongly per region (Appendix A – table A18). In all scenarios the global levels rise, especially in the CCM scenarios with large amounts. To put this into context, global eutrophication by nitrogen alone may exceed 135 million tonnes in 2030 (Smith, 2003). To arrive at total eutrophication potentials other sources of eutrophication need to be accounted for as well, but it indicates that bioenergy production is possibly a significant contribution.

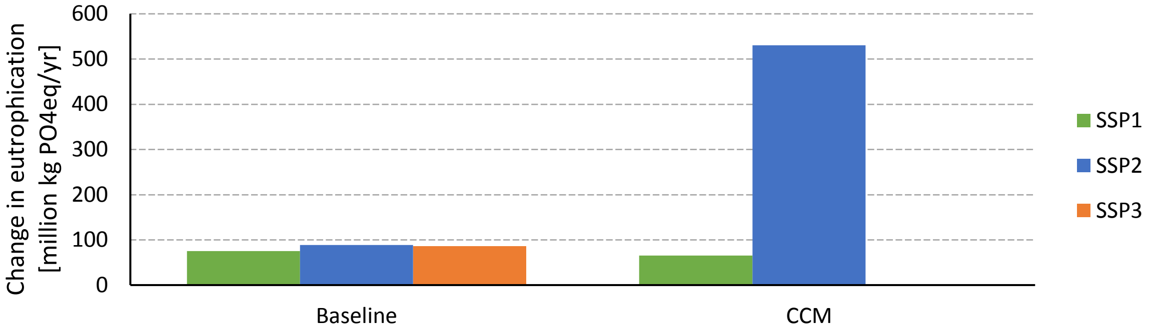

Figure 15 – Change in eutrophication by bioenergy production (world)

SDG 15 – Life on land

Bioenergy production yield

Bioenergy production yield changes (Appendix A – table A21) vary much per region and period (example for SSP2 in Table 12). As argued in the discussion (section 4.1), this is in part effect of two methodological aspects instead of actual yield developments. In the global yield changes one of these aspects is not present, which could explain the unrealistic high yield increases for some regions (up to 14% year on year).

Table 12 - Year-on-year biomass production yield changes by bioenergy use (SSP2)

		Baseline		**Climate change mitigation**	
		2010-2020	2020-2030	2010-2020	2020-2030
SSP2	World	4.4%	1.9%	3.9%	3.1%
	OECD90	7.2%	2.8%	5.4%	7.3%
	Reforming economies	6.0%	0.4%	-1.2%	10.9%
	Asia	1.9%	-3.4%	1.7%	-1.7%
	Middle East and Africa	5.8%	1.8%	5.4%	1.3%
	Latin America	-3.1%	9.9%	-4.2%	12.9%

3.2 SDG results

Shown in Figure 16 are the composite SDG indicator world results, the composite SDG indicator results per region are included in Appendix B – SDG results (tables B1 and B2). The main result is that the possible contribution of bioenergy to achieving the SDGs is depending on the context in which bioenergy is used. Under the SSP1 and SSP2 storylines, bioenergy use results in mostly positive contributions to the SDGs while under the SSP3 storyline the contribution is mostly negative. Furthermore, the composite SDG indicator performance is depending on developments in the entire society. The energy sector is only a part in this and bioenergy is only a minor part of the energy supply (Figure 4), the impact bioenergy can make on the SDGs is limited. The strong link between bioenergy and SDG 7 and 13 can be observed in the results, as the impact is in most scenarios strongest for these goals. The strong link with SDG 15 is only observed for SSP3 as under the SSP1 and SSP2 storylines forests are well protected.

Below the results are explained in more detail per scenario.

SSP1

Baseline

In the SSP1 baseline, bioenergy use either has no effect (SDG 15) or a positive (SDG 3, 7, 9, 13) effect on the sustainable development goals. However the impact is small to moderate for each goal, with a maximum of 4.3% benefit to SDG 7.

The limited impact of bioenergy use on achievement of the SDGs is a result of the SSP storyline: SSP1 is a 'green' scenario with low population growth, high technical developments and a preference for sustainable energy. Consequence of this is that the energy demand growth is limited in the first place and renewable energy is preferred regardless of bioenergy availability. The bioenergy that is consumed is mainly produced on abandoned agricultural lands, which limits the negative aspects.

Climate change mitigation

With a CCM scenario in place the results follow the same trend as in the baseline SSP1 scenario. Implementation of the CCM policy results in lower energy use compared to the baseline, of which bioenergy fulfils a smaller part (Figure 4). The smaller use of bioenergy use is not so much caused by the CCM policy, but rather an effect of the baseline scenario already being a 'green' scenario. To meet the climate target only moderate extra efforts are required over the baseline. The effect is a lower contribution of bioenergy on the SDGs in the CCM scenario compared to the baseline.

SSP2

Baseline

In the SSP2 storyline there is no strong preference for bioenergy. Without carbon tax incentives (baseline scenario) the increase in bioenergy use is moderate (24%). Bioenergy can therefore only impact the SDGs on a limited scale (max. 2.1% in case of SDG 7). Compared to SSP1, the absolute bioenergy consumption is higher in SSP2 baseline but the relative share in the energy system is lower. This is caused by strong increasing energy demand in SSP2 due to higher population growth and a lower rate of energy efficiency improvement compared to SSP1.

Climate change mitigation

With the introduction of a carbon tax under the CCM policy, bioenergy becomes much more competitive. This results in a high share in the energy supply (Figure 4). With a higher use the effect of bioenergy on the SDGs also increases (max. 20.8% in case of SDG 7). Included in SDG 13 and 15 are land use change effects, which despite the high bioenergy use are reported by IMAGE to be low. This is in part an effect of the SSP2 storyline, in which natural lands with high carbon stocks are mostly protected from conversion to bioenergy cropland. The land use change emissions by bioenergy are limited by this and this results in a net positive effect of bioenergy use on climate change (SDG 13).

SSP3

Baseline

The impact of bioenergy on the SDGs is, expect for SDG 7, negative. The positive contribution to SDG 7 is of low (1.5%) magnitude. Compared to the SSP2 baseline the impact to SDG 7 has even declined due to lower absolute bioenergy use and higher absolute total energy use in SSP3. This is result of differences between the SSP storylines (higher population growth and lower technological improvements in SSP3). The negative effects of bioenergy use are more pronounced compared to SSP1 and SSP2 as under SSP3 natural land, including high carbon stock land, is converted to agricultural land. The land use change emissions caused by the land conversion result in a net increase of global GHG emissions (4.3%). The net increase in GHG emissions propagate to a decrease composite indicator results for SDG 9, 13 and 15.

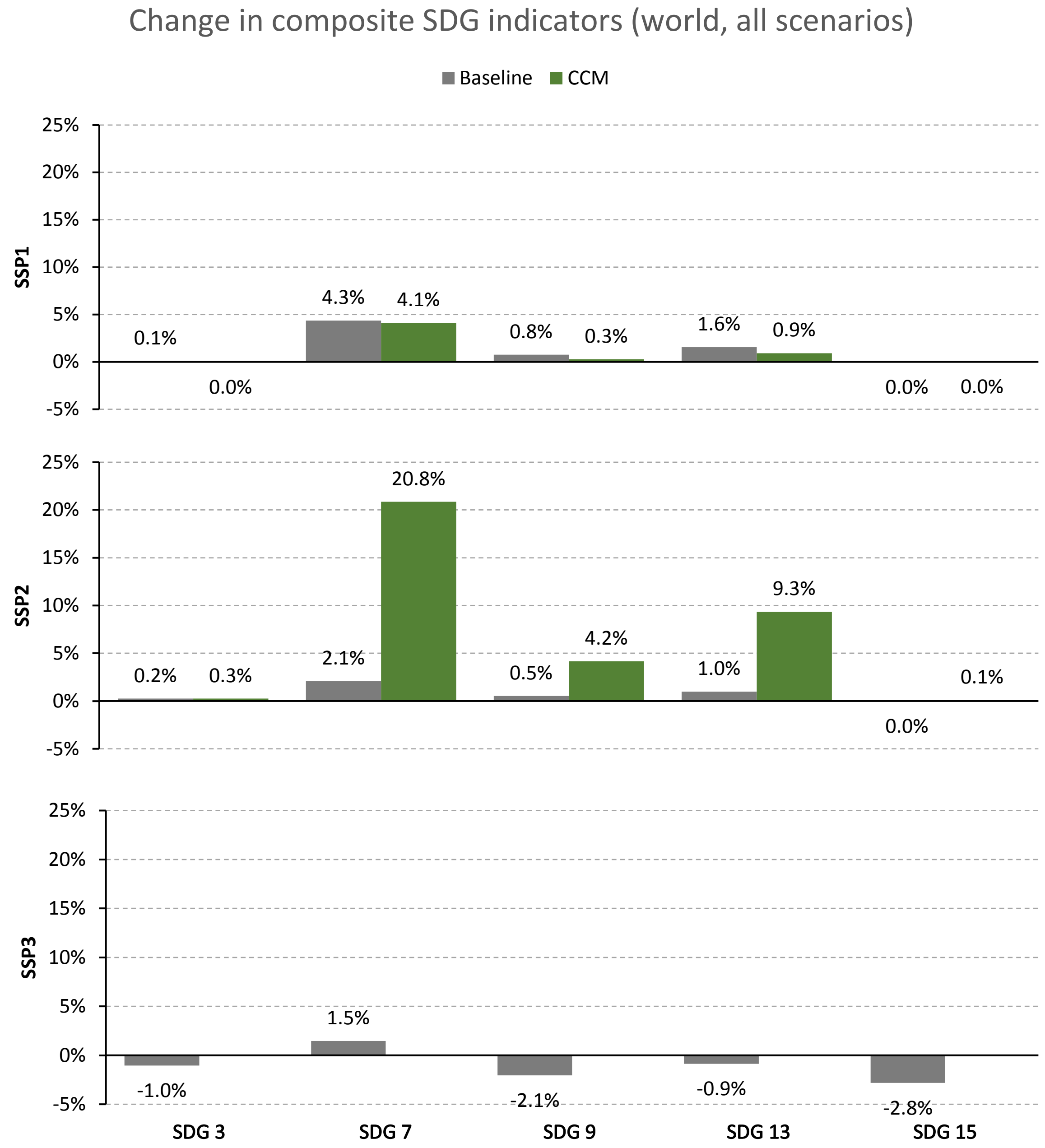

Figure 16 – Change in composite SDG indicators when allowing bioenergy use (positive = synergy, negative = trade-off)

3.3 Synergies and trade-offs

The composite SDG indicator results using the tier I and tier II indicators in Figure 16 present synergies as positive contribution and trade-offs as negative contribution. The trade-offs and synergies for these SDGs are discusses below per SSP scenario. For SDGs without composite indicator due to tier III classification of the individual indicators, the impact is assessed qualitatively.

SSP1

Under SSP1 bioenergy use is mostly in synergy with the SDGs, but not with big impact. As SSP1 is a 'green' storyline, the contribution that bioenergy can make is limited. This holds for both the baseline and the CCM scenario. Possible trade-offs are avoided in SSP1 by the implementation methods (most notably protection of natural land).

SSP2

With SSP2 being a less 'green' scenario there is more room for improvement, so bioenergy use can create stronger synergies with the SDGs. In the baseline scenario, there is a low incentive for bioenergy use which results in a small share of the energy supply. The synergies are therefore also limited. Implementation of a CCM policy creates stronger incentives and results in a higher share of the energy supply. The synergies increase accordingly and are high for energy and climate related goals (SDG 7 and 13). Even under the high bioenergy use in the CCM scenario, the bioenergy implementation methods under SSP2 avoid trade-offs.

SSP3

In the SSP3 storyline, bioenergy use is a trade-off with most SDGs. Although in SSP3 there is a lot of room for improvement, there are low restrictions on the implementation method of bioenergy. As result it is implemented in a poor way (most notably destruction of high carbon natural land), which reflects in the trade-offs.

SDGs without composite indicator

As water use is indispensable for biomass growth, it cannot be avoided by implementation methods and a trade-off with SDG 6 is likely for all SSP scenarios. Increased employment is expected by bioenergy use (see also discussion section 4.1), creating a synergy with SDG 8. As the amount of pollution depends on technological improvements and the implementation methods, the level of trade-offs with SDG 14 are expected to differ per scenario. Under the optimistic storyline of SSP1 the negative effects can be expected to be manageable, but will be more severe in the SSP3 storyline.

4 Discussion

In this section the weaknesses of the used methods and the implementation of bioenergy in IMAGE are discussed. In general, indicators and SDGs related to energy, land use and GHG emissions (so also climate change) are well developed. Indicators related to societal aspects and environmental (other than GHG emissions) aspects are less well developed. This is mostly a result of using data supplied by the IMAGE model. As IMAGE is primarily used to project changes in the energy sector and climate change impacts of society, these aspects are implemented the most extensive within the framework. This effect recurs in the tier classification of the indicators. The best developed indicators (tier I) are mostly indicators for SDG 7, 13 and 15 which are goals closely related to the energy sector, land use and GHG emissions. The least developed indicators (tier III) are mostly related to SDGs 6, 8 and 14 which are goals related to societal effects or indirect environmental effects. Covered with such limitations that assessment was not possible are indicators for SDG 1 and 2, which are directly related to societal aspects. Other research on the achievement of the SDGs is all in retrospect and based on statistical data (OECD, 2016; Sachs et al., 2016). No modelling limitations thus have been dealt with in these cases (but are replaced by gaps in availability of statistics).

In the following sections the methods and implementation are discussed for the individual indicators, for the composite SDG indicators and for the definition of synergies and trade-offs. Additionally, the effect of the chosen time horizon is discussed.

4.1 Indicator discussion

The used method is discussed for selected indicators. Indicators which are not mentioned below are regarded well developed, both in the used method as in the implementation in IMAGE.

Tier I

SDG 3 – Good health and well-being

Non-GHG air pollutants

The used method to account for non-GHG air pollution is limited in two aspects. The first is a limitation in detail caused by the scale of the assessed regions. Within the used method the effects of air pollution are averaged out over large regions, but in reality non-GHG air pollution is also a problem of local scale. The potential occurrence of local high levels of pollutants (hot spots such as cities or industrial areas) is thus not accounted for so the indicator may represent the impact of bioenergy too low compared to reality. Secondly by using HTP-equivalences only the effects of direct exposure are included, so impacts of bioenergy use on effects such as agricultural smog effects are left out.

SDG 7 – Affordable and clean energy

Energy price

In the used method, electricity prices are used as indicator for energy prices. Although bioenergy is in part used for electricity generation, another important aspect of bioenergy is conversion of biomass to liquid fuels. This is because bioliquids are the easiest option of replacing fossil energy in sectors where liquid fuel use is difficult to replace (e.g. aviation and heavy transport). Bioenergy induced price impacts in this category are not covered by the indicator directly, but only indirectly via price competition of primary energy sources.

Traditional biomass use

Within the IMAGE model, demand for traditional biomass is function of relative costs of different energy sources. Although this is a valid method for use in a model, not all effects that change biomass use in reality can be predicted by a model. For example, a lack of access to biomass for traditional use to local communities can occur by conversion of natural land to managed land.

Energy supply diversity

The Herfindahl-Hirschman Index used as indicator for energy supply diversity is not without critique. As put forward in Kruyt et al. (2009) there is no fundamental reason for use of an exponent of 2 in the index (equation 6), while change of this parameter would create different outcomes.

SDG 13 – Climate action

Non-renewable energy use

In the IMAGE model the use of carbon capture and storage (CCS) is allowed. This option is used after 2020 in the CCM scenarios, with the exact extent depending on the SSP. Because of this the amount of non-renewable energy should thus not be used as indicator for carbon emissions, but solely as indicator for dependency on finite energy sources.

SDG 15 – Life on land

Forest area

The used method only accounts for forest area and is not taking into account ecological value of forests. Bioenergy use can impact the ecological value of forest area in several ways. First, differences in types of forest are not accounted for. IMAGE models most of the bioenergy to be produced in Africa and Latin America, but the ecological value of forests in those areas is very different from e.g. taiga forest. Second, the spatial distribution of forest area is not accounted for while fragmentation could occur if bioenergy cropland is dividing forest areas. Last, the impact of bioenergy cropland on neighbouring forest areas due to nutrient pollution or changing water availability is excluded from the indicator.

Tier II

SDG 2 – Zero hunger

As explained in section 2.2, an explicit food-first principle is modelled within IMAGE. The result is that the impact of bioenergy use on food and feed production cannot be assessed with the current IMAGE model. The independency of SDG 2 progress from bioenergy as shown by the results are thus effect of model limitations. In section 5.1 recommendations for improvements of the IMAGE model are made to include bioenergy use effects on SDG 2 in IMAGE.
Beside the model limitations, the indicators for SDG 2 are regarded well-developed.

SDG 3 – Good health and well-being

Indoor smoke

In the used method, the burden of disease from using solid fuels is assumed to be independent of bioenergy use. However as observed that the traditional biomass use changes with a different rate compared to the population using solid fuels, it suggests that allowing bioenergy solid fuel is used for other applications than traditional use (e.g. pellets). The burden of disease of solid fuel use depends on the application in which the solid fuel is used (e.g. three-stone fire or iron stove with chimney), it follows that the assumption of constant burden of disease is not entirely correct. The indoor smoke indicator is thus probably showing results that are conservative, however the magnitude of the effect of changing burden of disease is uncertain.

SDG 9 – Industry, innovation and infrastructure

Freight

Within the IMAGE model, freight demand is determined based on GDP development and an energy price elasticity (Girod, van Vuuren, & Deetman, 2012). As GDP developments are set in the SSP scenarios, the freight demand is only affected by energy price changes due to biomass. No direct link to freight demand for bioenergy is thus included. As bioenergy requires considerable amounts of transport (from field to conversion facility and to the final use), the freight demand is thus likely to be underestimated.

Based on the formulation of UN goal 9.1 (IAEG-SDG, 2015), an increase in freight levels is regarded positive in this thesis. Although some aspects of increased freight are positive (e.g. increased employment and trade) there are also negative aspects (e.g. increase in emissions). The direction of freight developments which is regarded positive is thus depending on the assessors values.

Tier III

SDG 6 – Clean water and sanitation

Water footprint

The used method of calculating the bioenergy green water footprint is very sensitive to the made assumptions and additional literature data. First the water footprint of bioenergy (Table 6) differs per source, type of biomass and production location. The uncertainty of this input data is directly transferred to uncertainty of the water footprint output. Second the assumption that the water footprint is constant over time regardless of yield is a rough simplification.

Water footprint results of the used method are compared with literature values in Table 13. To put these values into context, the total human WF in the period 1996-2005 was on average 9087 km^3/yr (Hoekstra & Mekonnen, 2011). Mouratiadou et al. (2016) use an integrated modelling framework (part of which is the LPJmL module, also used in IMAGE) to project the water demand for energy and food under the SSP scenarios. Note that, although the SSP scenario assumptions are used, the results are different as a different energy model and water use assumptions are used. Chaturvedi et al. (2013) projects the impact of multiple climate change policies on irrigation water demand using an IAM (the Global Change Assessment Model (GCAM)). Included is a scenario in which a policy is limiting radiative forcing to 2.5 W/m^2 in 2100, which is assumed comparable to the SSP2 CCM scenario used in this thesis. The bioenergy WF varies over a wide range, again indicating the sensitivity to scenario and model differences. Although the method used in this thesis is very simple compared to the methods used in literature the results are plausible.

Table 13 - Comparison water footprint indicator results with literature values

Source	Scenario	Biomass [EJ/yr]	WF [km^3/yr]
This thesis	SSP2 CCM	91	381
Mouratiadou et al. (2016)	SSP2 2.6 W/m^2 policy	80	150
Chaturvedi et al. (2013)	2.5 W/m^2 policy	70	750

SDG 08 – Decent work and economic growth

Employment

As with the water footprint indicator of SDG 6 described above the used method for employment calculation is very sensitive to the literature input data. As shown in Table 7 the uncertainty of the employment rate in biomass production is high, consequentially the uncertainty of the employment results is high too.

By only including direct employment in biomass production, indirect employment effects of bioenergy use are neglected. However as shown in De la Rúa & Lechón (2016) direct employment in biomass production accounts for only 30% of all employment effects in biomass production and employment in supporting sectors is twice as high as employment in agriculture. This suggests that actual employment effects of bioenergy are far greater than direct employment in biomass production. However, negative indirect employment effects in other sectors are also neglected. For example, bioenergy use will probably reduce employment in competing energy supply sectors. Also in the agricultural sector jobs are possibly lost when farmers switch from food to biomass production. Bioenergy induced employment decreases will have a dampening effect on net employment creation by bioenergy.

SDG 13 – Climate action

Land use GHG emissions

As elaborated in the method section and shown by the results in Table 11, the timeframe over which land use GHG emissions are assessed play an important role to the results. However there is no fundamental reason for selection of a particular timeframe, so the results will always be partly subjective. It is argued that long time frames (up to 85 years) are preferred for assessing bioenergy land use emissions (Daioglou, 2016, Chapter 3). This implies that for this indicator a timeframe of 2010-2030, as used in the rest of the thesis, is too short. Despite this the allocation timeframe is usually in the order of 20-30 years (Daioglou, 2016, Chapter 3).

The used method accounts for land use emissions and bioenergy production of all bioenergy cropland present in the timeframe. However, ideally the land use emissions and bioenergy production of cropland created up to 2030 is accounted for. In case of the timeframes up to 2040 and 2050, effects of newly created cropland distort the land use GHG emission results of the cropland existing in 2030. The problem of unequally including the burdens (land use change emissions which occur early) and benefits (bioenergy production over longer period) is thus not completely solved by expanding the timeframe, but only shifted. Despite inclusion of new cropland, most bioenergy cropland is created around 2030 so the obtained results still show a decrease in land use GHG emissions for the longer timeframes. In section 5 an improved method to calculate land use GHG emissions is proposed.

For the 2010-2050 timeframe the land use GHG emissions are a minimum of 40 Mt CO2/EJ. To assess secondary energy emissions the conversion losses (the used method accounts for primary energy) and supply chain emissions need to be accounted for additionally. To put this into perspective, the direct emission factor for motor gasoline from fossil sources is 69 Mt CO2/EJ (Blok, 2009). This implies that when using bioenergy as liquid fuel it may not even be possible to reach a 40% reduction of emissions. In case of bioenergy use for electricity or heat generation the emission reduction may be larger.

With the land use GHG emissions indicator being classified as tier III, it is excluded from use in the composite SDG indicator. Main argument for this is the lack of no-bioenergy counterfactual, but side effect is that the uncertainty in this indicator is not propagated into the composite SDG indicator.

SDG 14 – Life below water

Nutrient pollution

Uncertainty in the nutrient pollution results arises from two methodological assumptions and the scale of assessment. The first assumption as elaborated in the indicator method is that the eutrophication potential per unit energy is constant over time. It is uncertain this will hold as by 2030 the experience in bioenergy crop production will be higher, which may lead to improved agricultural practices. Part of this can be higher fertilizer use efficiency and consequentially lower specific eutrophication potentials.

The second assumption in the nutrient pollution indicator method is use of second generation bioenergy only. In case first generation bioenergy is still used by 2030, the eutrophication potential will likely be higher compared to the current results as literature eutrophication potentials for first generation bioenergy are higher compared to second generation bioenergy (Clarens et al., 2010). With nutrient pollution evaluated on a scale of world regions, pollution is averaged over large regions (same effect as described in the discussion of 'Non-GHG air pollutants' indicator). With this approach the existence of nutrient pollution 'hot-spots' is thus overlooked.

SDG 15 – Life on land

Bioenergy production yield

The bioenergy production yield results (Appendix A – Table A21) show large differences both between regions and between scenarios. Two aspects are identified that could have added distortion of actual effects to the obtained results.

First aspect is trade of bioenergy between the regions. The used method accounts for bioenergy consumption (increases with imports, decreases with exports) and land area for bioenergy crop production (independent of trade). Energy trade will thus drive the indicator down for the producing region while increasing it in the importing region. The global results are not affected by this and are therefore more reliable.

Second aspect are yield developments as result of changes in the produced bioenergy crop type. For instance, advanced biofuels (produced from second generation energy crops such as woody feedstocks) have a higher conversion efficiency than regular biofuels (produced from first generation energy crops such as sugarcane). This would lead to a shift to lower yield in primary energy terms but a higher yield in secondary energy terms.

4.2 SDG discussion

Three important considerations need to be made with the used method for aggregation of single indicator results into a composite SDG indicator result. These are related to loss of details, double counting of effects and assignment of equal weights to all indicators and SDGs.

Loss of detail

Inherent to using a composite indicator result for the wide range of issues covered by the SDG is the omission of details. With assessment of a global composite indicator for a specific year, details are lost on regional level, indicator level and the indicator pathway.

Loss of indicator details are illustrated by Figure 17 and Figure 18, which show that the spread of indicator results per SDG can be wide. The widest spread of indicator results is found for SDG 7 (Figure 17 and Appendix A), while this spread is not shown by the composite indicator. Other SDGs have lower (however still significant) indicator result spreads. Due to the spread of indicator results, in SSP3 indicators for SDG 3, 9 and 13 (Figure 18) are not consistent in whether bioenergy makes a positive or negative contribution to the SDG. For the other scenarios (SSP1 and SSP2 both with and without bioenergy) the indicators per SDG indicate a uniform direction of movement (positive or negative).

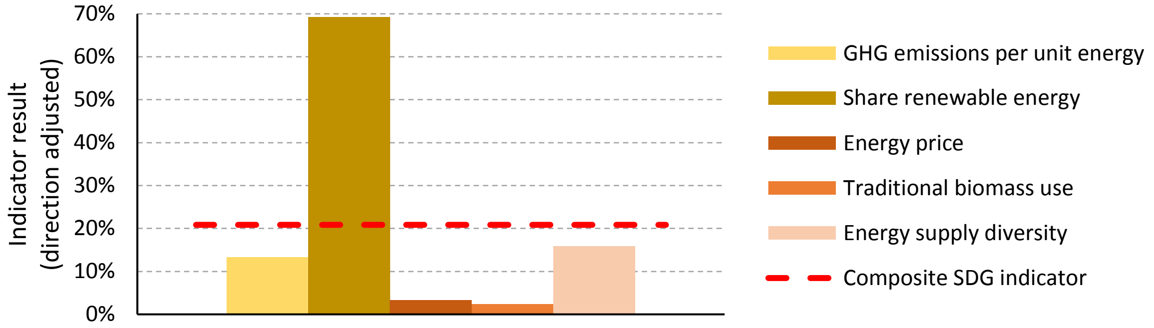

Figure 17 – SDG 7 composite indicator result breakdown (SSP2 CCM scenario)

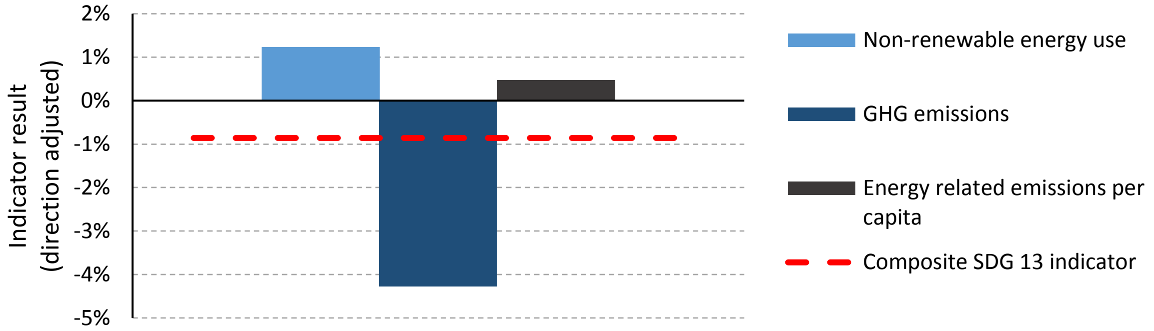

Figure 18 – SDG 13 composite indicator result breakdown (SSP3 baseline scenario)

Loss of regional details is caused by the aggregation of regions into a global indicator. It depends on the issue which is accounted for whether this is a positive or negative effect. For issues with a global impact regardless of the originating region this effect is positive. For issues with an impact limited to regional size this effect is negative. (e.g. regional GHG emission have a global impact, but water use is a local problem).

Loss of pathway detail is affecting indicators for effects with a long-lasting impact. Of the used indicators in this research, most vulnerable to this loss of detail are greenhouse gas emissions. The issue covered by this indicator (climate change) is not depending only on the annual emissions, but instead on the cumulative emissions over the complete pathway to that point. This is related especially to bioenergy, as land use change possibly leads to high emissions preceding reduced emissions. Depending on the assessment moment, this results in indicator results that is either too high (during land conversion) or too low (no land conversion, only bioenergy use).

Double counting

With a total of 22 indicators used in this research the risk of accounting an effect multiple times (double counting) exists. Double counting is possible on two levels: on research level by the methods used in this thesis and on model level by interaction of variable within IMAGE.

On research level, double counting originates in using the same variable in multiple indicators. This occurs in indicators for SDG 7 in which primary energy supply variables are used in the indicators energy supply, share renewable energy and traditional biomass use. The primary bioenergy crop supply variable is also double counted as it is used in indicators in SDGs 13, 14, 15 and 16.

On model level, assessment for double counting is more difficult identified due to the complex model dynamics of IMAGE and the use of readily supplied data. The multiple used variables that describe emission levels are exemplary for this. Although used in different terms (e.g. GHG emissions, GHG emissions per capita, GHG emissions per unit energy) the variables all share a common ultimate driver: GHG emissions. A second example are the variables that are price driven in IMAGE. As elaborated in the results and discussion section the price impact of bioenergy is observed in multiple indicators, such as freight demand and traditional bioenergy use.

To avoid double counting, the set of indicators per SDG has been selected subject to the sufficiency indicator requirement (section 2.3). However, as discussed above, double counting has not been avoided completely. Due the complex interaction of variables within IMAGE, the use of multiple variables per indicator (for some indicators) and aggregation into composite indicators (for some SDGs), it is difficult to quantify the effects of double counting. A possible method to check for this is a sensitivity analysis of the composite indicator results to some key variables such as GHG emissions or energy prices, but this was not possible within the time and scope of this research. Furthermore, as the SDGs are so highly interrelated by nature, it is questionable if double counting can be avoided completely.

Equal weights

Equal weights are used for all indicators and SDGs. However this may not be the best reflection of priorities in all personal or institutional discourses. Despite this the method is selected as it reflects the UNs discourse (it follows the UN proposal).

4.3 Synergies and trade-offs discussion

The single most important consideration of the synergies and trade-offs between bioenergy and the SDGs is that, as result of the used methods, not all aspects of bioenergy are covered in the results. As elaborated in the method section, tier III indicators are excluded from use in the synergies and trade-offs. As some of the most discussed aspects of bioenergy (e.g. land use change emissions) are covered in tier III they are thus omitted in the synergies and trade-offs. The qualitative assessment in the indicator method discussions has shown that effects of tier III indicators are mostly negative (water footprint, land use GHG emissions and nutrient pollution), so the synergies and trade-offs are likely to be to favourable to bioenergy.

A second consideration is that bioenergy use is the only assessed variable in this research. Therefore no comparative value (such as 'best') can be given. The results can only be used to mutually compare the implications of bioenergy use on the SDGs. Further not included are the possibilities to reach the same effects with other methods. For example, it could be much harder to reach the same benefits of bioenergy use on SDG 13 (climate action) with other measures, while the negative aspects of bioenergy use are averted with less effort.

5 Recommendations

As elaborated in section 2.2, the broad spectrum of aspects covered in IAMs make them particularly suitable of assessment of the SDGs. The IMAGE model selected for use in this research is particularly well-developed on emission and climate aspects so covers the SDGs related to these aspects particularly well. However, SDGs related to some social aspects currently lack cover in the IMAGE model.

Due to the wide cover and interrelated nature of the SDGs, proper incorporation of all sustainable development goals provides new challenges for IMAGE and (IAM) models as a whole. Models have to be improved in order to better incorporate more aspects of human and natural systems, with social and environmental effects in particular. To correctly implement this the inter-relationships between relevant aspects need to be better represented. This poses a significant difficulty to modellers who inherently have to make judgements during the selection of inter-relationships (choices of drivers and dependents). The inter-relationships as used in a model fundamentally impact model behaviour. Therefore the results and the potential insights can be depending on model characteristics.

In the first section recommendations are made to improve the representation of SDGs by model and method improvements. In the second section bioenergy policy recommendations are made to both increase synergies and limit trade-offs to the SDGs.

5.1 Model and method recommendations

In general it is recommended to focus improvement efforts in order of tier III, III and I. As tier III indicators are currently least developed and tier I indicators best, improvement in this order will yield the largest improvements first.

SDG 1 – No poverty

As explained in the indicator selection (section 2.3), poverty ratios are a scenario dependent input in the current IMAGE model. As result the impact of bioenergy deployment on poverty cannot be assessed within the current model setup. In order to include variance of poverty rates to model projected developments, a feedback system from model variables to the poverty rate should be created. As it is acknowledged that poverty ratios are important parameters of the SSP scenarios, a trade-off between dependency on the SSP scenario and the model feedback should be found. It is therefore suggested to create a bandwidth in which the poverty rate can be moved by the feedback system, with the bandwidths selected in such a way that no overlap can exist between the SSP scenarios. Possible driving variables for poverty rate change could for example be economic developments, employment developments (see IMAGE model recommendations for SDG 8 below) or food price developments. The most appropriate variable drivers and implementation method should be researched further.

SDG 2 – Zero hunger

Since the current IMAGE set-up towards bioenergy (section 2.2) includes a food-first principle, bioenergy use does not affect food production. Food and feed demand is calculated in the MAGNET module based on inputs from the SSP scenarios, after which all the required land for food and feed production is allocated in the LPJmL module. Though this method highlights the possible production of bioenergy without affecting food production, currently lacking is the inevitable price based competition between bioenergy and food and feed. To include price based competition, it is recommended to split the food and feed demand as calculated by MAGNET in a base demand and optional demand. The base supply represents the food and feed demand required to prevent famines, for which a food-first principle is appropriate as society is expected not to tolerate famines. The additional supply should represent extra food and feed demand from dietary changes based on prices (e.g. higher demand for meat due to low prices), for which competition with bioenergy is allowed. To determine the level of optional demand, a feedback link of bioenergy prices as calculated by TIMER can be used. The proposed model changes are shown in Figure 19, where the dotted system would replace the direct link between the MAGNET and LPJmL module.

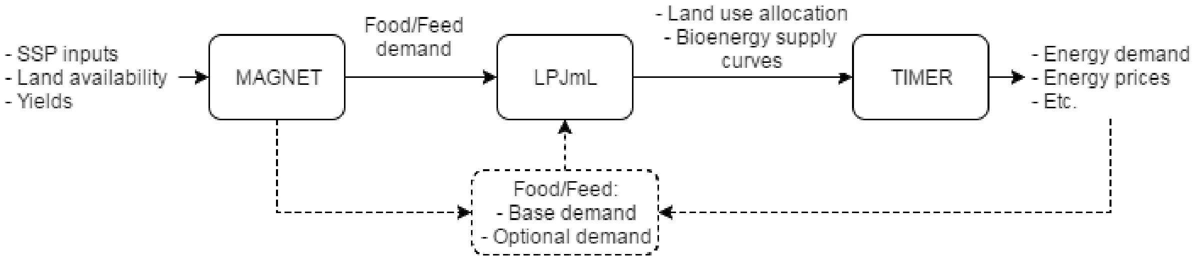

Figure 19 – Recommended IMAGE adjustment for SDG 2 (shown in dotted lines)

SDG 3 – Good health and well-being

Indoor smoke

With the used method the burden of disease is assumed constant, while as argued in the discussion section this is not entirely true to reality. It is thus recommended to include changes in burden of disease in the indicator performance. This can either be direct (the burden of disease itself) or indirect (variables that drive changes in the burden of disease such as traditional biomass use).

SDG 6 – Clean water and sanitation

Water footprint

As explained in the water footprint method (section 2.4), the current model setup assumes bioenergy crop cultivation to be unirrigated and therefore no direct water footprint of bioenergy is available. However, included in the LPJmL module is a hydrological module which dynamically calculates agricultural water demand as well as water availability and withdrawals (Gerten, Schaphoff, Haberlandt, Lucht, & Sitch, 2004). The LPJmL module accounts for the net water balance per grid cell as result of precipitation, interception loss and evapotranspiration by plants and soils (Gerten et al., 2004). In case of water surpluses the water flows to neighbouring grid cells in direction of rivers (Gerten et al., 2004). Since bioenergy crops are included in this water cycle, the impact of bioenergy use on water availability (green and blue water) can be accounted for by summation of changes (between scenarios with and without bioenergy use) in water flows between grid cells. As land area in use for bioenergy crop cultivation replaces natural land or other agricultural land with an accompanying water cycle, this proposed method accounts for net water use of bioenergy. This method also accounts for differences between bioenergy crop types, which are neglected by use of an average water footprint in the current method.

SDG 8 – Decent work and economic growth

Employment

As elaborated in the discussion (section 4.1) the used method is limited in representing changes in employment as it only accounts for direct employment in bioenergy crop production. As elaborated in the indicator discussion (section 4.1), indirect employment effects can be expected in other sectors. Next to the examples of other energy supply sectors and the agricultural sector, indirect effects could occur in for example the transportation sector, energy conversion sector and the chemicals sector. Two methods are possible to increase the cover of bioenergy use effects. The first method is expansion of the bottom-up approach of employment effects from the current single sector to additional sectors. Although being detailed, this method is laborious as many sectors should be included for adequate representation of bioenergy use impacts. The second method is a top-down approach by using the economic output of IMAGE to calculate labour demand for all economic activities. This method provides less detail however it includes all sectors so reduces the risk of missing impacts. Also, it is possibly less laborious compared to specifying the impact for many sectors individually. An first option to implement this method is by using an external IO model, which already is performed in existing research (de la Rúa & Lechón, 2016). A second option is to expand the MAGNET module for this purpose. Although MAGNET has a focus on the agricultural sector, it is a multi-regional, computable general equilibrium (CGE) model that covers the entire economy (Stehfest et al., 2014, sec. 4.2.1). It could thus also account for indirect changes in other sectors due to bioenergy use.

SDG 9 – Industry, innovation and infrastructure

Freight

The current freight demand is flawed as the underlying method relies on price-driven freight demand changes only (discussion section 4.1). The largest impact of bioenergy use on freight is expected in transportation from production areas to processing facility, as the energy density (both volume and mass) of biomass is low before processing into secondary forms such as liquids or pellets (Twidell & Weir, 2015). A first proposed method to account for this is a rough approximation by multiplying an average transportation distance from biomass production site to processing facility per unit bioenergy with the total amount of produced bioenergy. A second, more detailed proposed method is to separate the freight demand into regional and long distance freight. Regional freight effects can be determined using the spatial land use distribution as provided by the LPJmL module. By defining 'clusters' of grid cells allocated to biomass feedstock production with a processing facility located in the middle of each cluster, the transportation distance of bioenergy for each individual cell can be calculated. Combined with the bioenergy production level for each individual cell the total regional freight demand can be determined. Two possible methods for projection of the long distance, interregional freight demand are the use of TIMER data and the BIT-UU model. As interregional bioenergy trade flows are outputs of TIMER, they could serve as base for long distance bioenergy freight demand. In case the international biomass transportation model BIT-UU (Hoefnagels, 2014) is linked to IMAGE it could also project long distance bioenergy freight demand.

SDG 14 – Life below water

Nutrient pollution

First, local 'hot-spots' of nutrient pollution are overlooked with the current method (section 4.1). Inclusion of this effect can be implemented in IMAGE by use of the spatial land use allocation and water flows as calculated by the LPJmL module. Nutrient pollution loads to the water stream can be defined for each individual cell based on the land use type, after which cumulative nutrient pollution can be tracked per watershed or river by following the water flow path. This proposed method is not limited to eutrophication by bioenergy crop production, but can be used for multiple types of land use.

Second, the current method assumes the eutrophication potential to be constant over time. Advances in agricultural practices such as increase of fertilizer efficiency could lead to lower nitrification potentials and are neglected with this assumption. Already accounted for in the TIMER model are learning curves and exogeneous learning for technological developments. If the eutrophication potential is included in TIMER and linked to an appropriate learning curve, it can be made variable to time and the SSP storylines.

Third, an average eutrophication potential for all bioenergy crop types is used in the current method. As shown by the eutrophication potential per crop type in Table 8, in reality there is a wide spread of eutrophication potential values over the different crop types. A breakdown to a crop specific eutrophication potential would thus yield more accurate results.

SDG 15 – Life on land

Forest area

Lacking in the current research method for SDG 15 is inclusion of qualitative effects of forest change (section 4.1). Two indicator adjustments are proposed to better account for this. The first is adding a geographical location based forest quality adjustment. This forest quality adjustment could for example be based on the number of species a unit forest area can support. The second is a forest size adjustment. Forest sizes can be determined by using the spatial land use allocation output of the LPJmL module, assumed by size allocation is a difference between forest sizes to support species (e.g. top predators require large uninterrupted forests).

Land use GHG emissions

As elaborated in the discussion section, the land use GHG emissions results are distorted by cropland created after 2030. A simple method that excludes developments after 2030 is assumption of constant bioenergy production and land use GHG emissions at 2030 levels to the end of the time frame. However, this omits developments of bioenergy yields and gradual decrease of land us GHG emissions. Another, more detailed, possible method is use of the spatially explicit results of the LPJmL module. This would be by isolation of the land use GHG emissions and bioenergy production results of grid cells in use for bioenergy production by 2030 from results of other grid cells. With this method, the indicator result is still variable to developments after 2030 for the cropland in use by 2030, but undistorted by cropland created after 2030.

5.2 Bioenergy policy recommendations

The identified causes for differences in synergies and trade-offs between the scenarios provided insight in the interactions between bioenergy and the SDGs. With this insight, recommendations for bioenergy implementation in which synergies are maximised and trade-offs are limited can be provided.

SDG 7, 13 and 15 are affected to a large extent by the type of land bioenergy is produced on. To avoid trade-offs between bioenergy use and these SDGs, conversion of high carbon stock lands must be avoided (observed in SSP3). It is thus recommended to limit the bioenergy use to production on abandoned agricultural land or low carbon lands (observed in SSP1 and SSP2). The trade-off for SDG 6 is affected by the water footprint of the produced crop type and by the location of the bioenergy production. In case bioenergy production locations use crop types with a minimal increased water footprint compared to the previous vegetation, the trade-off is minimized. It is thus recommended to use bioenergy crop types matched to the production location. Bioenergy crop yields impact SDG 7, 13 and 15. As higher yields increases the synergy with SDG 7 and 13 and at the same time decreases the trade-off with SDG 15, high yielding crop types are recommended. The trade-off with SDG 14 depends on the eutrophication potential. To minimize this trade-off, it is recommended to apply cultivation methods and crop types with the lowest possible eutrophication potential.

It is acknowledged that some of these recommendations may be conflicting (e.g. high yields may go accompanied by high water footprints). Further research may be necessary to properly assess and quantify interactions between these recommendations and any further synergies and trade-offs.

6 Conclusion

As formulated in the research question, the aim of this research was to quantify the synergies and trade-offs on the SDGs by bioenergy use and how they differ under implementation of a climate change mitigation goal. In order to quantify the trade-offs and synergies, composite indicators for the SDGs related to bioenergy use have been constructed. Bioenergy use induced changes to the composite SDG indicators have been assessed for IMAGE model projections in both a baseline and climate change mitigation scenario in three possible alternative futures as described in the SSP storylines.

Synergies

There are considerable differences in possible synergies between the alternative futures. In the SSP1 (optimistic scenario) and SSP2 (middle-of-the-road scenario) futures, mostly synergies between the SDGs and bioenergy use occur. These are strongest for SDG 7 (affordable and clean energy) (out of the different scenarios maximum 21% move of composite SDG indicator in desired direction), SDG 9 (Industry, innovation and infrastructure) (maximum 4% move) and SDG 13 (climate action) (maximum 9% move).

Two main drivers for the synergies in SSP1 and SSP2 are identified. First, in SSP1 and SSP2 surplus agricultural lands are available for bioenergy crop production while natural lands (most importantly high carbon stock natural lands) are protected. With this land use change and consequently land use change emissions are avoided, leading to a net reduction of greenhouse gas emissions by bioenergy use. This has a positive effect on indicators which use variables that are related to greenhouse gas emissions. Second, by allowing bioenergy use, competition between energy sources increases which in turn decreases energy prices. This has a positive effect on indicators which use variables that are determined by an energy demand price curve.

Synergy differences between SSP1 and SSP2 are due to the storyline differences. Under SSP1 population growth is lower, technological advancements are higher and there is a higher preference for renewable energy. This results in higher synergies for SSP1 in the baseline.

Trade-offs

In the SSP3 (pessimistic) future, bioenergy use results in trade-offs with most SDGs. This is strongest for SDG 15 (life on land) with composite indicator decrease of 3%.

The main driver for the trade-offs is land use change. In the SSP3 storyline there is a high population growth and low technological development, which result in no abandonment of agricultural land. Combined with low protection of natural lands, bioenergy use results in conversion of natural land for biomass production. The land use change emissions that are accompanied by this result in a net increase of total greenhouse gas emissions by bioenergy use. This negative effect offsets the benefits of bioenergy use for most SDGs, resulting in trade-offs. However, the timeframe of accounting plays an important role as the land use change emissions occur early in the timeframe. With longer timeframes, more bioenergy is produced on the converted land which dampens the negative effect of the initial land use change emissions.

Impact of climate change mitigation

In the climate change mitigation scenarios, the average solar radiative forcing is limited to 2.6 W/m^2 in the year 2100. Within the IMAGE model this is achieved by implementation of a carbon price. The carbon price increases the competitiveness of bioenergy compared to other energy sources.

With SSP1 baseline already being a 'green' scenario in which the bioenergy potential is already used, the impact of climate change mitigation is low and the synergies are equal to the baseline. With a lower preference for bioenergy in SSP2 baseline, bioenergy use increases strongly as result of the increased competitiveness in the mitigation scenario. Consequently, the synergies with the

SDGs are increased (up to 21% for SDG 7, 19 percent point increase over baseline). Under SSP3, climate change mitigation is not assessed because it is not possible to reach the 2.6 W/m^2 target in this possible future.

Qualitative assessment of other synergies and trade-offs

For SDGs 6 (clean water and sanitation), 8 (decent work and economic growth) and 14 (life below water) no quantification of the trade-offs and synergies was possible. This is as the current model setup does not include indicators for these SDGs. Instead, the indicators are calculated using literature data with a scope limited to bioenergy production. Missing a counterfactual with this method, SDGs 6, 8 and 14 are assessed only qualitatively.

In case of SDG 6, a trade-off is possible since biomass cultivation for energy use may increase the water footprint. For SDG 8 a synergy is possible as biomass cultivation and processing requires substantial amounts of labour. However bioenergy use may also reduce work opportunities elsewhere (i.e. fossil fuel industry). Since bioenergy generally has a higher employment rate compared to other energy sources, the net employment effects of bioenergy use are possibly positive. For SDG 14 a trade-off is possible as, depending on the bioenergy crop type and agricultural practices, an increase of eutrophication of water can occur.

Method

In order to quantify and assess the trade-offs and synergies, it was required to formulate a consistent and transparent method (research sub-question 1). The devised method consists of identifying the relevant SDGs, selection of relevant and quantifiable indictors and the creation of composite SDG indicators. In the discussion section the limitations of the created method are identified. These are related to issues of detail, double counting and most importantly the use of a tiered classification due to a lack of data. The lack of data is due to the fact that though the SDGs aim to cover all/most aspects of human life and the natural environment, the IMAGE model places a greater emphasis on certain elements (i.e. greenhouse gas emissions). Other aspects (i.e. labour) are either not included dynamically (are exogenous) or modelled in a very aggregate manner.

Recommendations

Based on the discussion of the indicators, it has been found that IMAGE is well equipped to represent emission and climate aspects of the SDGs. It is less well developed to represent SDGs addressing social aspects. Multiple improvement options for better representation of the SDGs are elaborated. It is recommended to focus efforts for improvement on the indicators currently classified as tier III, as this would yield the biggest improvement.

Based on the observed differences in the synergies and trade-offs between the scenarios, recommendations on bioenergy implementation policies are made. In order to maximise synergies between bioenergy use and the SDGs, conversion of natural land for bioenergy production should be avoided. Furthermore, bioenergy crop types with low water footprints, low eutrophication effects and high yields are preferable.

If the IMAGE model could be improved using the recommendations, further research may be necessary to properly assess and quantify synergies and trade-offs between bioenergy use and the SDGs and the interactions of the bioenergy policy recommendations.

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8 References

Adams, R. H. (2004). Economic growth, inequality and poverty: Estimating the growth elasticity of poverty. *World Development*, *32*(12), 1989–2014. http://doi.org/10.1016/j.worlddev.2004.08.006

Anríquez, G., Daidone, S., & Mane, E. (2013). Rising food prices and undernourishment: A cross-country inquiry. *Food Policy*, *38*(1), 190–202. http://doi.org/10.1016/j.foodpol.2012.02.010

Blok, K. (2009). *Introduction to Energy Analysis* (2th ed.). Amsterdam: Techne Press.

Borek, R., Faber, A., & Kozyra, J. (2010). Water implications of selected energy crops cultivated on a field scale. *Journal of Food, Agriculture and Environment*, *8*(3–4 PART 2), 1345–1351.

Chaturvedi, V., Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., & Wise, M. (2013). Climate mitigation policy implications for global irrigation water demand. *Mitigation and Adaptation Strategies for Global Change*, 1–19. http://doi.org/10.1007/s11027-013-9497-4

Clarens, A. F., Resurreccion, E. P., White, M. A., & Colosi, L. M. (2010). Environmental life cycle comparison of algae to other bioenergy feedstocks. *Environmental Science and Technology*, *44*(5), 1813–1819. http://doi.org/10.1021/es902838n

Cornelissen, S., Koper, M., & Deng, Y. Y. (2012). The role of bioenergy in a fully sustainable global energy system. *Biomass and Bioenergy*, *41*, 21–33. http://doi.org/10.1016/j.biombioe.2011.12.049

Daioglou, V. (2016). *The role of biomass in climate change mitigation - Assessing the long-term dynamics of bioenergy and biochemicals in the land and energy systems.*

Dale, V. H., Efroymson, R. A., Kline, K. L., Langholtz, M. H., Leiby, P. N., Oladosu, G. A., … Hilliard, M. R. (2013). Indicators for assessing socioeconomic sustainability of bioenergy systems: A short list of practical measures. *Ecological Indicators*, *26*, 87–102. http://doi.org/10.1016/j.ecolind.2012.10.014

De Bruin, J. (2016). *The Sustainable Development Goals and Bioenergy*. Bsc. Thesis Biology. Utrecht University.

de la Rúa, C., & Lechón, Y. (2016). An integrated Multi-Regional Input-Output (MRIO) Analysis of miscanthus biomass production in France: Socio-economic and climate change consequences. *Biomass and Bioenergy*, *94*, 21–30. http://doi.org/10.1016/j.biombioe.2016.08.003

Desai, M. A., Mehta, S., & Smith, K. R. (2004). Indoor smoke from solid fuels: Assessing the environmental burden of disease at national and local levels. *Environmental Burden of Disease Series*, (4), 82.

Djomo, S. N., Kasmioui, O. EL, & Ceulemans, R. (2011). Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *GCB Bioenergy*, *3*(3), 181–197. http://doi.org/10.1111/j.1757-1707.2010.01073.x

Dollar, D., Kleineberg, T., & Kraay, A. (2016). Growth still is good for the poor. *European Economic Review*, *81*, 68–85. http://doi.org/10.1016/j.euroecorev.2015.05.008

Domac, J., Richards, K., & Risovic, S. (2005). Socio-economic drivers in implementing bioenergy projects. *Biomass and Bioenergy*, *28*(2), 97–106. http://doi.org/10.1016/j.biombioe.2004.08.002

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land Clearing and the Biofuel Carbon Debt. *Science*, *319*(5867), 1235–1238. http://doi.org/10.1126/science.1152747

Fritsche, U. R., & Iriarte, L. (2015). The

Sustainable Development Goals (SDGs) and Biomass in the EU: An Issues Brief, 45.

Gabrielle, B., Nguyen The, N., Maupu, P., & Vial, E. (2013). Life cycle assessment of eucalyptus short rotation coppices for bioenergy production in southern France. *GCB Bioenergy*, *5*(1), 30–42. http://doi.org/10.1111/gcbb.12008

Gasol, C. M., Gabarrell, X., Anton, A., Rigola, M., Carrasco, J., Ciria, P., & Rieradevall, J. (2009). LCA of poplar bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario. *Biomass and Bioenergy*, *33*(1), 119–129. http://doi.org/10.1016/j.biombioe.2008.04.020

GBEP. (2011). The Global Bioenergy Partnership Sustainability Indicators for Bioenergy. First edition.

Gerbens-Leenes, W., Hoekstra, A., & van der Meer, T. H. (2009a). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(25), 10219–23. http://doi.org/10.1073/pnas.0812619106

Gerbens-Leenes, Hoekstra, A. Y., & van der Meer, T. (2009b). The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics*, *68*(4), 1052–1060. http://doi.org/10.1016/j.ecolecon.2008.07.013

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., & Sitch, S. (2004). Terrestrial vegetation and water balance - Hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, *286*(1–4), 249–270. http://doi.org/10.1016/j.jhydrol.2003.09.029

Girod, B., van Vuuren, D. P., & Deetman, S. (2012). Global travel within the 2 degree C climate target. *Energy Policy*, *45*, 152–166. http://doi.org/10.1016/j.enpol.2012.02.008

Hák, T., Janoušková, S., & Moldan, B. (2016). Sustainable Development Goals: A need for relevant indicators. *Ecological Indicators*, *60*, 565–573. http://doi.org/10.1016/j.ecolind.2015.08.003

Hoefnagels, R. (2014). Bridging gaps in bioenergy - Deploying system analysis to investigate potential biomass supply , demand and greenhouse gas mitigation scenarios from a national, European and global perspective. (Doctoral dissertation).

Hoekstra, A. Y., & Mekonnen, M. M. (2011). The water footprint of humanity. *Proceedings of the National Academy of Sciences*, *109*(9), 3232–3237. http://doi.org/10.1016/B978-0-12-799968-5.00007-5

Howarth, R. W., Sharpley, A., & Walker, D. (2002). Sources of nutrient pollution to coastal waters in the United States: Implications for achieving coastal water quality goals. *Estuaries*, *25*(4), 656–676. http://doi.org/10.1007/BF02804898

Huijbregts, M. A. J., Thissen, U., Guinée, J. B., Jager, T., Kalf, D., Van De Meent, D., … Reijnders, L. (2000). Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA. *Chemosphere*, *41*(4), 541–573. http://doi.org/10.1016/S0045-6535(00)00030-8

IAEG-SDG. (2015). Report to the 47th Session of the Statistical Commission of the UN Economic and Social Council. *Interagency and Expert Group on Sustainable Development Goal Indicators*, *E/cn.3/201*(December), 1–39. http://doi.org/10.1017/S0020818300006640

ICSU - ISSC. (2015). *Review of Targets for the Sustainable Development Goals: The Science Perspective.* Paris: International Council for Science (ICSU).

IEA. (2013). *World Energy Outlook 2013. International Energy Agency.* http://doi.org/10.1787/20725302

IPCC. (2007). Climate Change 2007: Synthesis Report. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva, Switserland, 104pp. http://doi.org/10.1256/004316502320517344

IPCC. (2014). Climate change 2014: Synthesis report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]*, IPCC, Geneva, Switzerland, 151 pp.

Kruyt, B., van Vuuren, D. P., de Vries, H. J. M., & Groenenberg, H. (2009). Indicators for energy security. *Energy Policy*, *37*(6), 2166–2181. http://doi.org/10.1016/j.enpol.2009.02.006

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, *525*(7569), 367–71. http://doi.org/10.1038/nature15371

Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. *Environ. Sci.: Water Res. Technol.*, *1*(3), 285–297. http://doi.org/10.1039/C5EW00026B

Monti, A., Fazio, S., & Venturi, G. (2009). Cradle-to-farm gate life cycle assessment in perennial energy crops. *European Journal of Agronomy*, *31*(2), 77–84. http://doi.org/10.1016/j.eja.2009.04.001

Mouratiadou, I., Biewald, A., Pehl, M., Bonsch, M., Baumstark, L., Klein, D., … Kriegler, E. (2016). The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, *64*, 48–58. http://doi.org/10.1016/j.envsci.2016.06.007

Müller, A., Weigelt, J., Götz, A., Schmidt, O., Alva, Lobos, I., Matuschke, I., … Beringer, T. (2015). *The Role of Biomass in the Sustainable Development Goals : A Reality Check and Governance Implications*. Institute for Advanced Sustainability Issues (IASS). Potsdam.

Newbold, T., Hudson, L. N., Hill, S. L., Contu, S., Lysenko, I., Senior, R. a, … Purvis, A. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*, 45–69. http://doi.org/10.1038/nature14324

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., … Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. http://doi.org/10.1016/j.gloenvcha.2015.01.004

OECD. (2016). *Measuring Distance to the SDGs Targets - A pilot assessment of where OECD countries stand*. Paris.

PBL. (2017). IMAGE 3.0 Documentation - Water. Retrieved March 15, 2017, from http://themasites.pbl.nl/models/image/index.php/Water

Sachs et al. (2016). *SDG index and dashboards - Global report*. New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., … Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, *319*(5867), 1238–1240. http://doi.org/10.1126/science.1151861

Seckler, D., Barker, R., & Amarasinghe, U. (1999). Water Scarcity in the Twenty-First Century. *Water Resources Development*, *15*(1/2), 29–42. http://doi.org/10.1080/07900629948916

Serra, T., & Zilberman, D. (2013). Biofuel-related price transmission literature: A review. *Energy Economics*, *37*, 141–151. http://doi.org/10.1016/j.eneco.2013.02.014

Singh, V., & Fehrs, J. (2001). The Work That Goes into Renewable Energy. *Renewable Energy Policy Project*, *13*, 28.

Smith, V. (2003). Eutrophication of freshwater and coastal marine ecosystems - a global problem. *Environmental Science and Pollution Research*, *10*(2), 126–139. http://doi.org/10.1065/espr2002.12.142

Stechow, C. von, Minx, J. C., Riahi, K., Jewell, J., McCollum, D. L., Callaghan, M. W., … Baiocchi, G. (2016). 2oC and the SDGs: United they stand, divided they fall? *Environmental Research Letters*, *11*(3), 34022. http://doi.org/10.1088/1748-9326/11/3/034022

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., … Prins, A. G. (2014). *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications.*

Thornley, P., Rogers, J., & Huang, Y. (2008). Quantification of employment from biomass power plants. *Renewable Energy*, *33*(8), 1922–1927. http://doi.org/10.1016/j.renene.2007.11.011

Twidell, J., & Weir, T. (2015). *Renewable energy resources* (3th ed.). Routledge.

UN. (2016). Sustainable Development Goals - Communication materials. Retrieved October 27, 2016, from http://www.un.org/sustainabledevelopment/news/communications-material/

UNEP. (2008). *Green Jobs: Towards decent work in a sustainable, low-carbon world.* Washington.

UNFCCC. (2008). Kyoto Protocol Reference Manual on accounting of emissions and assigned amount. In *United Nations Framework Convention on Climate Change* (p. 130). http://doi.org/10.5213/jkcs.1998.2.2.62

UNFCCC. (2015). Paris Agreement. *21st Conference of the Parties.* http://doi.org/FCCC/CP/2015/L.9

United Nations. (2015a). The Millennium Development Goals Report. *United Nations*, 72. http://doi.org/978-92-1-101320-7

United Nations. (2015b). Transforming our world: The 2030 agenda for sustainable development, *A/RES/70/1.*

van Vuuren, D., van Ruijven, B. J., Girod, & et al. (2014). *Energy supply and demand. In E. Stehfest, D. van Vuuren, T. Kram & A.F. Bouwman (Eds.), Integrated Assessment of Global Environmental Change with IMAGE 3.0 pp. 71.* The Hague: PBL Netherlands Environmental Assessment Agency.

Van Vuuren, Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., van den Berg, M., Harmsen, M., … Tabeau, A. (2015). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, 1–14. http://doi.org/10.1016/j.gloenvcha.2016.05.008

Wei, M., Patadia, S., & Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, *38*(2), 919–931. http://doi.org/10.1016/j.enpol.2009.10.044

WHO. (2016). Household air pollution and health - Fact sheet N°292. Retrieved February 7, 2017, from http://www.who.int/mediacentre/factsheets/fs292/en/

Zalasiewicz, J. A. N., Williams, M., Steffen, W., & Crutzen, P. (2010). The new world of the anthropocene. *Environmental Science and Technology*, *44*(7), 2228–2231. http://doi.org/10.1021/es903118j

9 Appendix

A. Indicator results

A1. SDG 2 – Food price

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Index (2005=1)		%		Index (2005=1)		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	OECD90	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Ref. economies	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Asia	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	M. East & Africa	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Latin America	0.00	0.00	0%	0%	0.00	0.00	0%	0%
SSP2	World	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	OECD90	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Ref. economies	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Asia	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	M. East & Africa	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Latin America	0.00	0.00	0%	0%	0.00	0.00	0%	0%
SSP3	World	0.21	0.48	20%	49%				
	OECD90	0.14	0.28	15%	33%				
	Ref. economies	0.13	0.32	14%	35%				
	Asia	0.33	0.86	26%	63%				
	M. East & Africa	0.09	0.22	10%	26%				
	Latin America	0.13	0.29	14%	34%				

A2. SDG 2 – Cereal yield

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Ton d.m./ha/yr		%		Ton d.m./ha/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	OECD90	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Ref. economies	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Asia	-0.01	-0.01	0%	0%	-0.01	-0.01	0%	0%
	M. East & Africa	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Latin America	0.00	0.00	0%	0%	0.00	0.00	0%	0%
SSP2	World	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	OECD90	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Ref. economies	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Asia	-0.01	-0.01	0%	0%	-0.02	-0.02	0%	0%
	M. East & Africa	0.00	0.00	0%	0%	0.00	0.00	0%	0%
	Latin America	0.00	0.00	0%	0%	0.00	0.00	0%	0%
SSP3	World	0.06	0.07	2%	2%				
	OECD90	0.31	0.38	6%	7%				
	Ref. economies	0.07	0.04	3%	2%				
	Asia	0.21	0.17	5%	3%				
	M. East & Africa	0.03	0.14	1%	6%				
	Latin America	-0.18	-0.19	-5%	-4%				

A3. SDG 3 – Non-GHG air pollution

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	HTP		%		HTP		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.26	-0.09	0%	0%	0.10	0.34	0%	0%
	OECD90	0.01	-0.17	0%	-1%	-0.04	-0.09	0%	-1%
	Ref. economies	-0.01	0.04	0%	0%	-0.04	0.07	0%	1%
	Asia	-0.06	-0.14	0%	0%	-0.08	0.12	0%	0%
	M. East & Africa	0.19	0.13	1%	1%	0.13	0.05	1%	0%
	Latin America	0.13	-0.03	1%	0%	0.13	0.09	1%	1%
SSP2	World	-0.06	-0.43	0%	0%	-1.13	-0.15	-1%	0%
	OECD90	-0.04	-0.43	0%	-2%	-0.11	-0.60	0%	-4%
	Ref. economies	-0.01	0.02	0%	0%	0.05	0.00	0%	0%
	Asia	-0.27	-0.46	0%	-1%	-0.78	-0.80	-1%	-1%
	M. East & Africa	0.18	0.20	1%	1%	-0.24	0.57	-1%	3%
	Latin America	0.09	0.15	1%	1%	-0.08	-0.12	-1%	-1%
SSP3	World	3.52	4.21	2%	2%				
	OECD90	0.18	-0.14	1%	-1%				
	Ref. economies	-0.04	-0.08	0%	-1%				
	Asia	0.45	0.52	1%	1%				
	M. East & Africa	2.07	2.38	8%	8%				
	Latin America	0.85	1.48	5%	9%				

A4. SDG 3 – Indoor smoke

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Million persons		%		Million persons		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-0.65	-1.75	0%	0%	-0.92	-2.46	0%	0%
	OECD90	-0.01	0.07	0%	0%	0.02	0.11	0%	0%
	Ref. economies	-0.02	-0.08	0%	0%	-0.04	-0.10	0%	0%
	Asia	-0.43	-1.52	0%	0%	-0.69	-2.16	0%	0%
	M. East & Africa	-0.09	-0.14	0%	0%	-0.06	-0.16	0%	0%
	Latin America	-0.10	-0.09	0%	0%	-0.15	-0.16	0%	0%
SSP2	World	-2.97	-8.15	0%	0%	-4.95	-14.00	0%	0%
	OECD90	0.01	0.07	0%	0%	-0.02	0.09	0%	0%
	Ref. economies	-0.03	-0.09	0%	0%	-0.18	-0.21	0%	0%
	Asia	-2.73	-6.57	0%	0%	-4.72	-14.21	0%	-1%
	M. East & Africa	-0.19	-1.34	0%	0%	-0.18	-0.19	0%	0%
	Latin America	-0.03	-0.21	0%	0%	0.15	0.53	0%	0%
SSP3	World	-2.29	-9.69	0%	0%				
	OECD90	0.00	0.05	0%	0%				
	Ref. economies	-0.03	-0.11	0%	0%				
	Asia	-2.06	-8.16	0%	0%				
	M. East & Africa	-0.17	-1.14	0%	0%				
	Latin America	-0.04	-0.33	0%	0%				

A5. SDG 6 – Water footprint

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	km^3/yr		%		km^3/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	22.54	58.49	31%	44%	20.79	43.37	38%	42%
	OECD90	0.07	0.04	10%	1%	0.30	-0.70	51%	-14%
	Ref. economies	-0.04	0.07	-4%	19%	-0.10	-0.38	-9%	-52%
	Asia	4.89	13.71	92%	82%	3.85	12.29	49%	74%
	M. East & Africa	15.16	43.72	31%	53%	12.12	20.83	43%	80%
	Latin America	2.46	0.95	15%	3%	4.61	11.34	28%	20%
SSP2	World	22.18	77.66	19%	32%	-73.38	289.10	-34%	316%
	OECD90	0.26	4.60	16%	49%	-2.86	8.32	-56%	67%
	Ref. economies	0.12	0.76	7%	18%	-7.66	-0.81	-80%	-33%
	Asia	4.25	25.80	36%	74%	-13.55	69.50	-44%	432%
	M. East & Africa	15.48	56.53	19%	36%	-21.12	171.18	-18%	544%
	Latin America	2.07	-10.04	10%	-28%	-28.20	40.91	-54%	141%
SSP3	World	16.07	42.67	15%	19%				
	OECD90	-1.11	12.91	-36%	65%				
	Ref. economies	-0.95	0.22	-23%	7%				
	Asia	5.31	9.62	49%	21%				
	M. East & Africa	13.96	19.41	22%	15%				
	Latin America	-1.14	0.51	-4%	2%				

A6. SDG 7 – GHG emissions per unit energy

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Mt CO$_2$/yr		%		Mt CO$_2$/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.21	-0.58	0%	-1%	0.12	-0.15	0%	0%
	OECD90	0.13	-0.10	0%	0%	-0.17	-0.21	-1%	-1%
	Ref. economies	0.00	0.10	0%	0%	-0.18	-1.42	0%	-3%
	Asia	0.26	-1.64	0%	-2%	0.43	-0.24	1%	0%
	M. East & Africa	0.22	-0.10	0%	0%	0.04	0.72	0%	2%
	Latin America	0.55	0.62	2%	2%	0.54	0.46	2%	2%
SSP2	World	0.27	-0.17	1%	0%	-1.44	-4.47	-3%	-13%
	OECD90	0.15	-0.38	0%	-1%	-0.51	-3.40	-2%	-14%
	Ref. economies	-0.01	-0.04	0%	0%	-1.37	-8.51	-3%	-20%
	Asia	0.35	-0.50	1%	-1%	-2.86	-5.56	-5%	-12%
	M. East & Africa	0.21	0.46	1%	1%	-0.35	-1.88	-1%	-10%
	Latin America	0.75	0.99	3%	4%	-0.60	-3.34	-2%	-15%
SSP3	World	0.32	-0.13	1%	0%				
	OECD90	0.12	-0.28	0%	-1%				
	Ref. economies	0.07	-0.60	0%	-1%				
	Asia	0.44	-0.23	1%	0%				
	M. East & Africa	0.20	0.35	1%	1%				
	Latin America	1.07	0.46	3%	1%				

A7. SDG 7 – Share renewable energy

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Percent point change		%		Percent point change		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.19	1.49	2%	13%	0.12	1.27	1%	10%
	OECD90	0.26	0.85	4%	10%	0.20	0.31	3%	3%
	Ref. economies	0.02	0.58	0%	8%	-0.34	2.23	-4%	23%
	Asia	-0.03	1.77	0%	17%	-0.05	1.43	0%	12%
	M. East & Africa	0.82	3.39	5%	20%	0.34	1.90	2%	12%
	Latin America	0.20	0.12	1%	1%	0.74	1.58	4%	7%
SSP2	World	0.02	1.04	0%	8%	2.45	9.24	19%	69%
	OECD90	0.28	1.18	4%	14%	1.51	6.72	22%	77%
	Ref. economies	-0.18	0.54	-2%	7%	4.24	10.68	82%	203%
	Asia	-0.37	0.95	-2%	8%	3.45	7.77	24%	58%
	M. East & Africa	0.71	2.69	3%	10%	1.57	14.36	6%	59%
	Latin America	-0.10	-1.71	0%	-7%	0.63	11.72	3%	51%
SSP3	World	-0.09	0.77	-1%	6%				
	OECD90	0.25	1.07	3%	12%				
	Ref. economies	-0.46	0.34	-6%	5%				
	Asia	-0.41	0.73	-3%	6%				
	M. East & Africa	0.50	1.04	2%	4%				
	Latin America	-0.48	-0.32	-2%	-2%				

A8. SDG 7 – Energy price

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	US$2005/MWh		%		US$2005/MWh		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-0.07	-0.04	-1%	-1%	-0.07	-0.07	-1%	-1%
	OECD90	-0.02	-0.04	0%	0%	0.00	-0.07	0%	-1%
	Ref. economies	0.01	-0.02	0%	0%	0.00	0.03	0%	0%
	Asia	-0.12	-0.03	-2%	-1%	-0.15	-0.10	-2%	-1%
	M. East & Africa	-0.13	-0.09	-3%	-2%	-0.17	-0.11	-3%	-2%
	Latin America	-0.08	-0.07	-1%	-1%	0.05	-0.05	1%	-1%
SSP2	World	-0.08	-0.05	-1%	-1%	0.06	-0.33	1%	-3%
	OECD90	-0.02	-0.06	0%	-1%	0.13	-0.37	2%	-4%
	Ref. economies	0.01	-0.02	0%	0%	-0.06	-0.84	-1%	-7%
	Asia	-0.15	-0.03	-3%	0%	-0.01	-0.27	0%	-3%
	M. East & Africa	-0.13	-0.10	-3%	-2%	-0.10	-0.13	-1%	-2%
	Latin America	-0.09	-0.11	-2%	-2%	0.27	-0.22	5%	-3%
SSP3	World	-0.08	-0.05	-1%	-1%				
	OECD90	-0.01	-0.06	0%	-1%				
	Ref. economies	0.00	-0.02	0%	0%				
	Asia	-0.16	-0.04	-3%	-1%				
	M. East & Africa	-0.13	-0.08	-3%	-2%				
	Latin America	-0.11	-0.07	-2%	-1%				

A9. SDG 7 – Traditional biomass use

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	EJ/yr		%		EJ/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-0.19	-0.76	-1%	-5%	-0.20	-0.71	-1%	-5%
	OECD90	0.00	-0.04	0%	-1%	-0.01	-0.05	0%	-2%
	Ref. economies	0.00	-0.02	0%	-2%	0.00	-0.02	0%	-2%
	Asia	-0.11	-0.37	-1%	-6%	-0.10	-0.30	-1%	-6%
	M. East & Africa	-0.05	-0.23	-1%	-5%	-0.05	-0.24	-1%	-6%
	Latin America	-0.04	-0.10	-2%	-6%	-0.04	-0.10	-2%	-7%
SSP2	World	-0.13	-0.40	0%	-1%	-0.41	-0.82	-1%	-2%
	OECD90	0.00	-0.03	0%	-1%	-0.02	-0.07	-1%	-3%
	Ref. economies	0.00	-0.02	0%	-2%	-0.01	-0.04	-1%	-4%
	Asia	-0.07	-0.14	0%	-1%	-0.20	-0.37	-1%	-2%
	M. East & Africa	-0.03	-0.13	0%	-1%	-0.09	-0.18	-1%	-2%
	Latin America	-0.02	-0.09	-1%	-3%	-0.09	-0.17	-3%	-6%
SSP3	World	-0.04	-0.12	0%	0%				
	OECD90	0.00	0.00	0%	0%				
	Ref. economies	0.00	-0.01	0%	-1%				
	Asia	-0.02	-0.04	0%	0%				
	M. East & Africa	-0.01	-0.04	0%	0%				
	Latin America	-0.01	-0.03	0%	-1%				

A10. SDG 7 – Energy supply diversity

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	HHI		%		HHI		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.00	-0.02	0%	-2%	0.00	-0.01	0%	-5%
	OECD90	0.00	-0.01	0%	-1%	0.00	0.00	-1%	-1%
	Ref. economies	0.00	-0.01	0%	-1%	0.00	-0.03	0%	-8%
	Asia	0.00	-0.02	0%	-2%	0.00	-0.01	1%	-3%
	M. East & Africa	-0.01	-0.02	-1%	-2%	0.00	-0.01	-1%	-4%
	Latin America	-0.01	0.00	-1%	0%	-0.01	-0.01	-2%	-4%
SSP2	World	0.00	0.00	0%	0%	-0.01	-0.04	-4%	-16%
	OECD90	0.00	-0.01	0%	-1%	-0.01	-0.04	-2%	-14%
	Ref. economies	0.00	0.00	0%	0%	-0.02	-0.07	-8%	-21%
	Asia	0.00	-0.01	0%	-1%	-0.02	-0.04	-7%	-15%
	M. East & Africa	-0.01	-0.01	-1%	-1%	-0.01	-0.04	-3%	-17%
	Latin America	0.00	0.00	0%	0%	0.00	-0.02	0%	-12%
SSP3	World	0.00	0.00	0%	0%				
	OECD90	0.00	-0.01	0%	-1%				
	Ref. economies	0.00	0.00	0%	0%				
	Asia	0.00	0.00	0%	0%				
	M. East & Africa	0.00	0.00	0%	0%				
	Latin America	0.00	0.00	0%	0%				

A11. SDG 8 – Employment

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	FTE/yr		%		FTE/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	11,143	28,632	32%	45%	10,250	21,324	40%	44%
	OECD90	36	34	11%	2%	148	-312	53%	-14%
	Ref. economies	-15	33	-3%	21%	-40	-179	-8%	-51%
	Asia	2,361	6,635	94%	84%	1,887	5,974	51%	76%
	M. East & Africa	7,498	21,307	32%	55%	5,958	10,118	44%	82%
	Latin America	1,263	624	16%	4%	2,298	5,723	29%	22%
SSP2	World	10,212	35,852	19%	32%	-54,354	125,306	-45%	245%
	OECD90	121	2,127	16%	49%	-1,809	2,675	-64%	38%
	Ref. economies	54	352	7%	18%	-4,459	-607	-83%	-44%
	Asia	1,964	11,937	35%	74%	-9,226	30,680	-53%	341%
	M. East & Africa	7,125	26,109	19%	35%	-20,880	76,345	-32%	435%
	Latin America	947	-4,673	10%	-28%	-17,980	16,214	-62%	100%
SSP3	World	15,839	37,219	37%	42%				
	OECD90	-298	7,725	-24%	96%				
	Ref. economies	-142	365	-9%	27%				
	Asia	3,383	8,036	77%	44%				
	M. East & Africa	11,467	18,893	45%	37%				
	Latin America	1,428	2,200	14%	21%				

A12. SDG 9 – GHG emissions per unit added value

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Kg CO_2eq./ US\$2005		%		Kg CO_2eq./ US\$2005		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.00	-0.01	0%	-1%	0.00	0.00	0%	0%
	OECD90	0.00	0.00	0%	-2%	0.00	0.00	0%	-1%
	Ref. economies	0.00	0.00	0%	0%	0.00	-0.01	0%	-2%
	Asia	0.00	-0.01	0%	-2%	0.00	0.00	0%	0%
	M. East & Africa	0.01	0.00	1%	0%	0.01	0.00	1%	1%
	Latin America	0.01	0.00	1%	-1%	0.01	0.02	1%	4%
SSP2	World	0.00	0.00	0%	-1%	-0.01	-0.02	-2%	-6%
	OECD90	0.00	-0.01	-1%	-2%	0.00	-0.02	-1%	-10%
	Ref. economies	0.00	0.00	0%	0%	-0.02	-0.07	-1%	-10%
	Asia	0.00	-0.01	0%	-1%	-0.03	-0.04	-3%	-7%
	M. East & Africa	0.02	0.01	1%	1%	-0.02	0.04	-1%	5%
	Latin America	0.00	0.02	0%	2%	-0.02	-0.01	-2%	-3%
SSP3	World	0.04	0.03	4%	4%				
	OECD90	0.00	0.00	1%	0%				
	Ref. economies	0.01	-0.01	0%	-1%				
	Asia	0.02	0.01	1%	1%				
	M. East & Africa	0.35	0.26	17%	15%				
	Latin America	0.13	0.16	10%	15%				

A13. SDG 9 – Freight

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	bn ton*km/yr		%		bn ton*km/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-3	453	0%	0%	-11	545	0%	0%
	OECD90	-1	272	0%	0%	-14	294	0%	0%
	Ref. economies	1	19	0%	0%	0	70	0%	1%
	Asia	-2	114	0%	0%	3	112	0%	0%
	M. East & Africa	0	35	0%	0%	0	37	0%	0%
	Latin America	0	14	0%	0%	0	32	0%	0%
SSP2	World	-4	500	0%	0%	138	3315	0%	3%
	OECD90	-2	333	0%	1%	94	2186	0%	4%
	Ref. economies	-2	26	0%	0%	12	198	0%	3%
	Asia	1	95	0%	0%	21	556	0%	2%
	M. East & Africa	0	30	0%	0%	3	180	0%	1%
	Latin America	-1	16	0%	0%	7	195	0%	2%
SSP3	World	5	235	0%	0%				
	OECD90	2	163	0%	0%				
	Ref. economies	0	9	0%	0%				
	Asia	2	39	0%	0%				
	M. East & Africa	1	16	0%	0%				
	Latin America	0	8	0%	0%				

A14. SDG 13 – Non-renewable energy use

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	EJ/yr		%		EJ/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-4.15	-12.43	-1%	-2%	-3.53	-9.94	-1%	-2%
	OECD90	-2.44	-4.10	-1%	-3%	-2.11	-3.02	-1%	-2%
	Ref. economies	-0.11	-0.26	0%	0%	-0.18	-1.45	0%	-3%
	Asia	-1.00	-6.31	-1%	-3%	-0.65	-4.23	0%	-2%
	M. East & Africa	-0.38	-1.28	-1%	-2%	-0.43	-0.72	-1%	-1%
	Latin America	-0.22	-0.48	-1%	-1%	-0.16	-0.52	-1%	-2%
SSP2	World	-3.48	-9.94	-1%	-2%	-12.09	-39.25	-3%	-9%
	OECD90	-2.65	-5.66	-1%	-3%	-2.09	-13.84	-1%	-10%
	Ref. economies	-0.13	-0.34	0%	-1%	-1.10	-4.79	-2%	-11%
	Asia	-0.24	-3.01	0%	-1%	-7.40	-15.62	-4%	-9%
	M. East & Africa	-0.34	-0.64	-1%	-1%	-0.71	-2.32	-2%	-5%
	Latin America	-0.12	-0.29	0%	-1%	-0.78	-2.69	-3%	-10%
SSP3	World	-2.64	-7.36	-1%	-1%				
	OECD90	-2.40	-4.55	-1%	-3%				
	Ref. economies	-0.09	-0.43	0%	-1%				
	Asia	0.08	-1.80	0%	-1%				
	M. East & Africa	-0.29	-0.30	-1%	0%				
	Latin America	0.06	-0.27	0%	-1%				

A15. SDG 13 – GHG emissions

Scenarios	→	Baseline				Climate change mitigation			
↓	Unit →	Mt CO_2eq/year		%		Mt CO_2eq/year		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	27	-694	0%	-1%	35	-63	0%	0%
	OECD90	-51	-194	0%	-2%	-51	-121	0%	-1%
	Ref. economies	-13	-14	0%	0%	-15	-66	0%	-2%
	Asia	-2	-437	0%	-2%	41	-24	0%	0%
	M. East & Africa	55	-8	1%	0%	35	29	1%	1%
	Latin America	42	-36	1%	-1%	29	125	1%	4%
SSP2	World	-2	-453	0%	-1%	-1010	-2345	-2%	-6%
	OECD90	-79	-306	-1%	-2%	-166	-994	-1%	-10%
	Ref. economies	-4	-21	0%	0%	-55	-338	-1%	-10%
	Asia	-2	-302	0%	-1%	-640	-1198	-3%	-7%
	M. East & Africa	68	75	1%	1%	-65	283	-1%	5%
	Latin America	20	107	0%	2%	-85	-102	-2%	-3%
SSP3	World	2513	2917	4%	4%				
	OECD90	171	69	1%	0%				
	Ref. economies	20	-36	0%	-1%				
	Asia	317	231	1%	1%				
	M. East & Africa	1395	1626	17%	15%				
	Latin America	615	1029	10%	15%				

A16. SDG 13 – Land use GHG emissions

Scenarios	→	Baseline			Climate change mitigation		
↓	Unit →	Mt CO_2/EJ			Mt CO_2/EJ		
	Timeframe →	2010 - 2030	2010 - 2040	2010 - 2050	2010 - 2030	2010 - 2040	2010 - 2050
SSP1	World	119	64	41	189	83	40
	OECD90	-255	-68	-69	-6195	-3839	139
	Ref. economies	-72	11	14	-32	107	-16
	Asia	84	95	77	119	104	70
	M. East & Africa	69	46	34	138	56	33
	Latin America	-5083	43	26	258	72	32
SSP2	World	95	50	40	109	64	50
	OECD90	637	46	14	-356	9	18
	Ref. economies	1872	-305	137	-21	2834	39
	Asia	-34	38	53	132	70	55
	M. East & Africa	70	51	47	76	60	48
	Latin America	-154	44	25	-149	79	58
SSP3	World	1642	607	232			
	OECD90	1014	390	190			
	Ref. economies	4503	3043	354			
	Asia	370	216	114			
	M. East & Africa	1991	587	232			
	Latin America	-12866	-13001	442			

A17. SDG 13 – Energy related emissions per capita

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	t CO_2eq/person/yr		%		t CO_2eq/person/yr		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.01	-0.03	0%	-1%	0.00	-0.01	0%	-1%
	OECD90	0.01	-0.03	0%	-1%	-0.03	-0.03	-1%	-1%
	Ref. economies	0.00	0.01	0%	0%	-0.02	-0.13	0%	-3%
	Asia	0.01	-0.06	0%	-2%	0.01	-0.01	1%	0%
	M. East & Africa	0.00	-0.01	0%	0%	0.00	0.02	0%	2%
	Latin America	0.02	0.03	2%	2%	0.02	0.02	2%	2%
SSP2	World	0.01	-0.02	0%	-1%	-0.07	-0.20	-3%	-13%
	OECD90	0.01	-0.07	0%	-2%	-0.07	-0.38	-2%	-14%
	Ref. economies	0.00	-0.01	0%	0%	-0.12	-0.66	-3%	-20%
	Asia	0.01	-0.02	1%	-1%	-0.10	-0.18	-5%	-12%
	M. East & Africa	0.00	0.01	0%	1%	-0.01	-0.05	-1%	-10%
	Latin America	0.03	0.05	2%	3%	-0.03	-0.14	-2%	-16%
SSP3	World	0.02	-0.01	1%	0%				
	OECD90	0.01	-0.06	0%	-1%				
	Ref. economies	0.00	-0.07	0%	-1%				
	Asia	0.02	-0.01	1%	0%				
	M. East & Africa	0.01	0.01	0%	1%				
	Latin America	0.05	0.02	3%	1%				

A18. SDG 14 – Nutrient pollution

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	million kg PO_4eq/year		%		million kg PO_4eq/year		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	32	75	28%	29%	21	65	21%	35%
	OECD90	0	-8	6%	-45%	2	-4	190%	-18%
	Ref. economies	0	-1	0%	-92%	0	-4	0%	-98%
	Asia	12	21	82%	57%	11	24	43%	64%
	M. East & Africa	17	68	21%	51%	5	27	9%	51%
	Latin America	2	-5	14%	-7%	3	22	14%	32%
SSP2	World	31	88	18%	19%	-67	530	-26%	309%
	OECD90	0	1	2%	4%	-11	33	-81%	183%
	Ref. economies	0	0	42%	-9%	-5	-1	-86%	-38%
	Asia	9	26	30%	35%	-5	125	-11%	358%
	M. East & Africa	19	96	16%	36%	2	256	1%	426%
	Latin America	2	-34	13%	-38%	-48	118	-73%	211%
SSP3	World	35	85	21%	21%				
	OECD90	2	18	83%	46%				
	Ref. economies	0	1	0%	34%				
	Asia	16	39	55%	47%				
	M. East & Africa	15	37	13%	15%				
	Latin America	2	-10	12%	-23%				

A19. SDG 15 – Forest area

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Million ha		%		Million ha		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	-0.97	-2.20	0%	0%	-0.50	-1.05	0%	0%
	OECD90	-0.67	-0.48	0%	0%	-0.68	-0.48	0%	0%
	Ref. economies	-0.05	-0.02	0%	0%	-0.05	0.04	0%	0%
	Asia	-0.17	-0.46	0%	0%	-0.18	-0.50	0%	0%
	M. East & Africa	-0.28	-0.48	0%	0%	-0.05	-0.32	0%	0%
	Latin America	0.20	-0.76	0%	0%	0.46	0.21	0%	0%
SSP2	World	-0.54	-1.05	0%	0%	0.35	-2.58	0%	0%
	OECD90	0.23	-0.16	0%	0%	-0.26	-1.16	0%	0%
	Ref. economies	0.19	0.09	0%	0%	1.01	0.24	0%	0%
	Asia	-0.12	-0.32	0%	0%	-0.09	-0.53	0%	0%
	M. East & Africa	-0.53	-0.31	0%	0%	-0.38	-0.52	0%	0%
	Latin America	-0.32	-0.34	0%	0%	0.07	-0.62	0%	0%
SSP3	World	-87.52	-137.19	-2%	-4%				
	OECD90	-21.64	-39.91	-2%	-4%				
	Ref. economies	-17.85	-25.69	-1%	-2%				
	Asia	-13.40	-22.53	-3%	-6%				
	M. East & Africa	-21.77	-31.57	-9%	-15%				
	Latin America	-12.86	-17.49	-2%	-3%				

A20. SDG 15 – Agricultural land area

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	Million ha		%		Million ha		%	
	Year →	2020	2030	2020	2030	2020	2030	2020	2030
SSP1	World	0.93	2.25	0%	0%	0.57	1.13	0%	0%
	OECD90	0.67	0.48	0%	0%	0.68	0.48	0%	0%
	Ref. economies	0.03	0.02	0%	0%	0.06	-0.04	0%	0%
	Asia	0.17	0.46	0%	0%	0.18	0.50	0%	0%
	M. East & Africa	0.26	0.54	0%	0%	0.10	0.40	0%	0%
	Latin America	-0.19	0.76	0%	0%	-0.46	-0.21	0%	0%
SSP2	World	0.57	1.19	0%	0%	-0.29	2.65	0%	0%
	OECD90	-0.22	0.15	0%	0%	0.26	1.17	0%	0%
	Ref. economies	-0.27	-0.09	0%	0%	-1.01	-0.23	0%	0%
	Asia	0.16	0.33	0%	0%	0.09	0.55	0%	0%
	M. East & Africa	0.59	0.45	0%	0%	0.42	0.51	0%	0%
	Latin America	0.31	0.35	0%	0%	-0.05	0.65	0%	0%
SSP3	World	89.55	139.44	1%	2%				
	OECD90	21.51	39.73	1%	2%				
	Ref. economies	16.92	24.77	2%	3%				
	Asia	13.80	22.70	1%	1%				
	M. East & Africa	24.45	34.72	1%	2%				
	Latin America	12.87	17.53	1%	1%				

A21. SDG 15 – Bioenergy production yield

Scenarios →		Baseline				Climate change mitigation			
↓	Unit →	GJ/ha/yr		% (y-o-y)		GJ/ha/yr		% (y-o-y)	
	Year →	2020	2030	2010-2020	2020-2030	2020	2030	2010-2020	2020-2030
SSP1	World	-20	-80	5.2%	1.3%	-88	-40	5.6%	0.8%
	OECD90	-23	-970	7.5%	8.2%	551	-90	16.7%	3.4%
	Ref. economies	4	-1163	-0.5%	-5.1%	12	-1873	-0.3%	-5.7%
	Asia	-66	-115	7.4%	-3.4%	-64	-58	5.7%	-3.8%
	M. East & Africa	-53	-16	6.5%	0.2%	-155	-126	5.2%	2.2%
	Latin America	-6	-84	-2.9%	9.0%	-54	39	0.1%	1.8%
SSP2	World	-2	-66	4.4%	1.9%	132	105	3.9%	3.1%
	OECD90	-70	-294	7.2%	2.8%	-386	455	5.4%	7.3%
	Ref. economies	69	-85	6.0%	0.4%	-27	42	-1.2%	10.9%
	Asia	-35	-169	1.9%	-3.4%	388	24	1.7%	-1.7%
	M. East & Africa	-11	2	5.8%	1.8%	166	-10	5.4%	1.3%
	Latin America	7	-127	-3.1%	9.9%	-112	325	-4.2%	12.9%
SSP3	World	-77	-118	6.0%	1.4%				
	OECD90	544	-210	13.8%	-4.1%				
	Ref. economies	20	13	3.7%	0.4%				
	Asia	-138	15	11.6%	-2.0%				
	M. East & Africa	-176	-131	7.3%	1.3%				
	Latin America	-4	-253	-4.0%	4.6%				

B. SDG results

B1. SDG results baseline scenario

Scenarios →		Baseline					
↓	SDGs →	2	3	7	9	13	15
SSP1	World	-0.03%	0.10%	4.34%	0.76%	1.55%	-0.04%
	OECD90	-0.02%	0.49%	2.60%	1.02%	1.61%	-0.04%
	Ref. economies	0.00%	-0.13%	1.99%	0.26%	0.20%	0.00%
	Asia	-0.07%	0.22%	5.70%	0.97%	2.13%	-0.07%
	M. East & Africa	-0.02%	-0.29%	5.69%	0.12%	0.86%	-0.11%
	Latin America	0.02%	0.21%	1.16%	0.43%	-0.03%	-0.08%
SSP2	World	-0.04%	0.25%	2.09%	0.52%	0.99%	-0.02%
	OECD90	0.01%	1.01%	3.54%	1.38%	2.37%	-0.01%
	Ref. economies	0.01%	0.04%	1.87%	0.37%	0.38%	0.01%
	Asia	-0.11%	0.47%	2.21%	0.64%	1.02%	-0.05%
	M. East & Africa	-0.08%	-0.33%	2.51%	-0.30%	-0.30%	-0.09%
	Latin America	-0.03%	-0.41%	-1.29%	-0.77%	-1.46%	-0.04%
SSP3	World	-23.83%	-1.03%	1.47%	-2.05%	-0.86%	-2.82%
	OECD90	-13.15%	0.30%	3.01%	-0.10%	1.14%	-2.98%
	Ref. economies	-16.79%	0.49%	1.41%	0.36%	0.83%	-2.33%
	Asia	-29.84%	-0.15%	1.48%	-0.33%	0.12%	-3.59%
	M. East & Africa	-10.28%	-4.18%	1.06%	-7.53%	-5.22%	-8.21%
	Latin America	-19.37%	-4.19%	-0.15%	-7.59%	-5.30%	-1.94%

B2. SDG results climate change mitigation scenario

Scenarios →		Climate change mitigation					
↓	SDGs →	2	3	7	9	13	15
SSP1	World	-0.04%	-0.04%	4.12%	0.27%	0.92%	-0.01%
	OECD90	0.00%	0.21%	1.57%	0.88%	1.48%	-0.03%
	Ref. economies	0.00%	-0.36%	7.17%	1.37%	2.73%	0.01%
	Asia	-0.12%	0.04%	4.45%	0.21%	0.87%	-0.03%
	M. East & Africa	-0.03%	-0.13%	4.20%	-0.18%	-0.35%	-0.04%
	Latin America	0.02%	-0.28%	3.24%	-1.57%	-1.18%	0.04%
SSP2	World	-0.03%	0.25%	20.85%	4.16%	9.34%	0.12%
	OECD90	0.00%	1.77%	22.29%	7.15%	11.47%	0.04%
	Ref. economies	0.02%	0.21%	51.27%	6.58%	13.83%	0.42%
	Asia	-0.16%	1.06%	17.93%	4.12%	9.03%	0.01%
	M. East & Africa	0.02%	-1.57%	17.82%	-2.10%	3.40%	-0.05%
	Latin America	0.01%	0.34%	17.51%	2.49%	9.25%	0.11%
SSP3	World	-	-	-	-	-	-
	OECD90	-	-	-	-	-	-
	Ref. economies	-	-	-	-	-	-
	Asia	-	-	-	-	-	-
	M. East & Africa	-	-	-	-	-	-
	Latin America	-	-	-	-	-	-