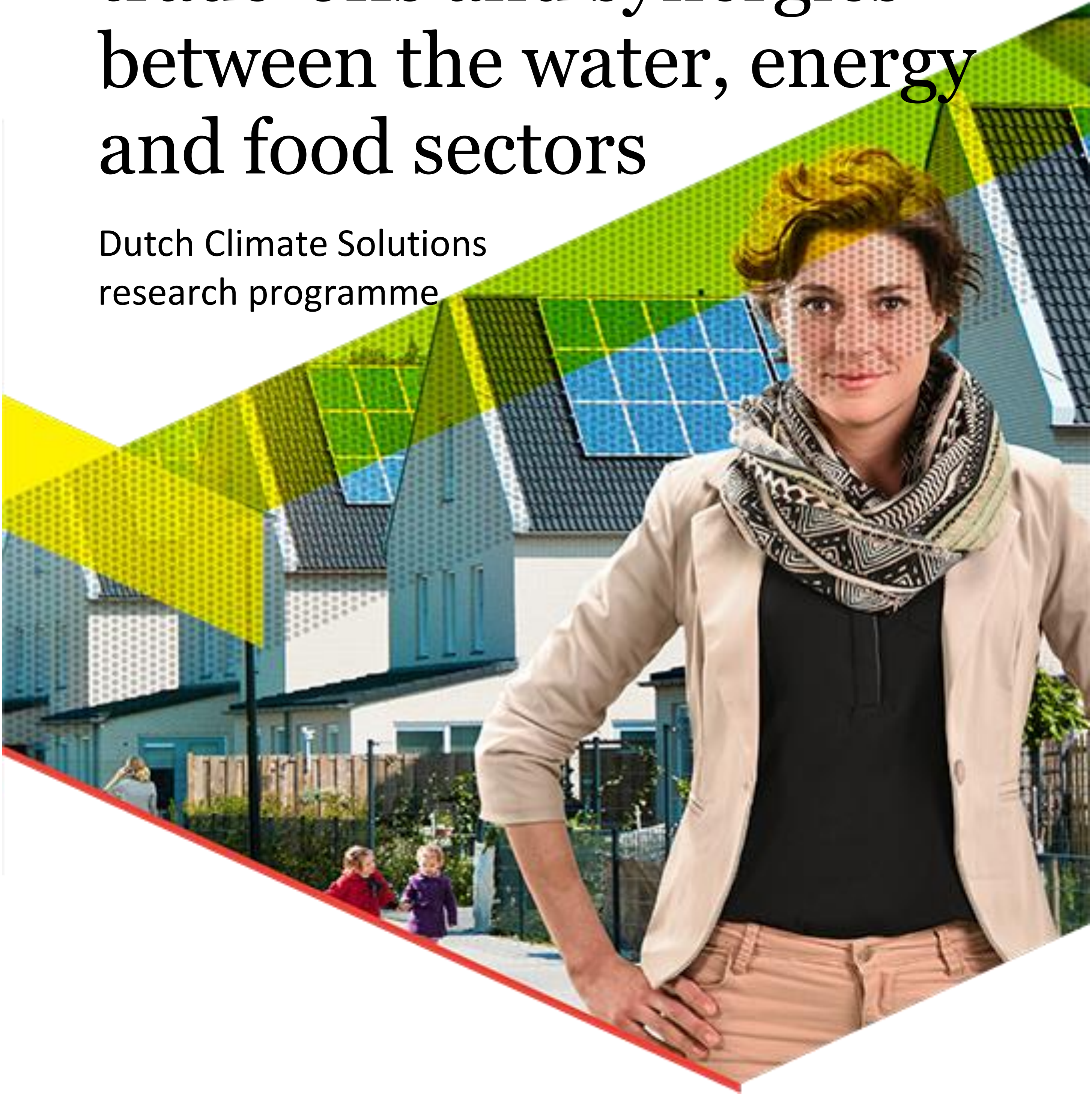
Operationalizing the WEF nexus: quantifying the trade-offs and synergies between the water, energy and food sectors

Dutch Climate Solutions
research programme



ECN-E--18-036 - March 2018

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Preface

This report is deliverable D27 of the Dutch Climate Solutions research programme. The programme acts as a platform for the Energy research Centre of the Netherlands (ECN) to support the Netherlands Directorate-General for International Cooperation (DGIS) in the realisation of Dutch policy objectives concerning poverty reduction and sustainable development. Support is delivered through the provision of demand-led, product-driven research and knowledge development. Particular attention is paid to expanding the contribution of Dutch expertise, innovation and technology to international climate assistance.

The main question address within this programme is how to leverage climate and private sector investments for sustainable and climate smart development, for with the consideration of the water-energy-food nexus is key. Accordingly key research questions dealt with are: a) How do we create a sustainable and effective balance in the water, energy and food sectors to achieve the Sustainable Development Goals, in the face of climate change, and b) what is the role and potential of climate finance to bring about transformative change in developing countries?

The program combines mutually reinforcing research and recommendations on the level of multilateral finance architecture, Dutch development aid and the Dutch climate technology sector to propose an integrated approach to support the climate technology sector and explore climate finance mechanisms through which the Dutch water-food-energy sectors can export their Climate Smart Solutions.

The Dutch Climate Solutions programme is funded by the Netherlands Ministry of Foreign Affairs and implemented by a consortium coordinated by the ECN. The consortium comprises the following organisations:

- Energy research Centre of the Netherlands (ECN)
- Deltares
- Stichting DLO, Wageningen UR
- Duisenberg School of Finance (until 1 October 2015).

The Dutch Climate Solutions programme is registered under ECN project number 5.2734.

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Abstract

The purpose of this research is to develop an analytical and modelling approach that allows for the quantification of trade-offs between the water, energy and food nexus at different scales; allowing to go from national analysis of nexus stress by identifying and quantifying key intersectoral claims and trade-offs, up to a more detailed and even local specific analysis of the trade-offs. These trade-offs and the system understanding created by following the proposed steps for the analysis of nexus stress, inform them the design of Climate Smart Solutions and Strategies that make use of the most powerful leverage points and introduce or exploit existing synergies between the water-energy-food sectors.

The national and local scales analyses following the proposed methodology have been applied to Ethiopia. At the national scale the integration has been done by making use of system analysis techniques in combination with the use of diverse modelling techniques for the quantification of the key trade-offs identified.

The soft-linking Deltares Water Allocation Model (Ribasim) and TIAM-ECN model for optimization of Energy Systems allowed for the quantification of trade-offs between the water and the energy sectors given the national plans to make significant increase in hydropower dams. This modelling exercise was complemented with excel calculations to quantify the trade-off between biomass production for energy and land available for food production, as well as to quantify the complex linkages between water and food security.

Last but not least, the economic analysis of trade-offs developed which builds on the so-called Vulnerability Framework (AGO, 2005) allowed the comparison of alternative adaptation investments and demonstrated that taking into account in the business case of an adaptation measure a nexus approach (accounting for the cost and benefits in other sectors) could improve the financial viability of such projects. The method developed and tested for Ethiopia making use of the TIAM-ECN and Ribasim modelling results could enable multisectoral investments in adaptation.

At the local level in the second part of 2017 a nexus analysis was undertaken making use of RIBASIM and LEAP models along with excel based agriculture production models to evaluate whether the planned Industrial Park for sesame processing, in Bae’ker, near Humera, Tigray, will create any significant trade-offs between the water, food and energy sectors, also in view of climate change. This research is following a collaborative modelling approach and aims to help local actors to come to a climate smart and diversified economy and develop a strategy for

economic growth in Humera that is also sustainable in terms of water, energy and food resources. The findings of this analysis are made available in separate report.

This multi-scale approach for analysis of nexus trade-off can be used either by donors, multilaterals to analyse and test at national and local level whether certain sectoral investments being planned are Climate Smart and advance the synergetic achievement of water-food and energy related SDG’s. The methodological approach developed and illustrated for the case of Ethiopia can also support governments in the generation of alternative solutions and changes in the design of these projects so that future nexus stresses and vulnerabilities are reduced to a minimum.

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Executive Summary

Rapidly growing demand and the globally uneven distribution of water, energy and food are leading to increasing competition for these resources. The effects of climate change pose an additional challenge, as heavy flooding in coastal areas and severe droughts in more arid regions could further exacerbate this competition and seriously impede economic growth. So far, energy, food and water challenges have mainly been addressed within the sectors concerned. This has resulted in policies and interventions that focus primarily on individual sectors, rather than considering the broader cross-sectoral impact. This lack of coordination, dialogue and collaboration among sectors can significantly affect the efficiency and effectiveness of policies and may also prevent appropriate measures from being taken. There is thus an urgent need to address these challenges simultaneously and develop an integrated approach. Balancing the trade-offs between these sectors will be essential if we are to achieve sustainable development and ensure water, energy and food security.

This study aims to develop a conceptual and methodological framework that allows for the quantification of the interactions and trade-offs between the water, energy and food sectors and to design and evaluate climate smart solutions that benefit(or at least not negatively affect) all three sectors. This framework draws on the vast experience and expertise of the three consortium partners: Energy research Centre of the Netherlands ECN, Deltares and Wageningen University & Research. The framework was applied to a case study in Ethiopia at the national level and one at the regional level in Humera district in the province of Tigray. The latter case study is reported in a separate report.

The study started with a literature review to assess existing and established research on the water, energy and food security nexus, with the objective of making an inventory of existing cases in which food security, water, energy and climate change are combined in one approach, and identifying the most relevant interactions between the three sectors. The findings of the review served as the starting point for the development of the conceptual framework.

Based on the outcome of the literature review, a conceptual and methodological framework was developed to identify and quantify the linkages between the three sectors and to handle the complexity of it. To develop this framework that can be shared among all relevant stakeholders, use has been made of system analysis and group model building techniques. System analysis was used to develop the conceptual models that portray the various interactions, cause-effect relationships, feedbacks and time delays between and within the water, energy and food systems. Once these conceptual models have been developed, system dynamics can be used to better

understand the behaviour of these complex systems over time. Departing from this conceptual framework the methodological approach adopted for this study consists of the following main steps:

1. Defining the problem
2. Forecasting and management of climate uncertainty
3. Analysis of trade-offs and synergies: identifying the critical links
4. Formulating climate smart strategies: making use of leverage points and synergies.

The conceptual framework was applied to Ethiopia. The Ribasim/Tiam/Water-limited crop model set was used to quantify the interactions between the WEF sectors and to analyse the long-term integrated demand-supply strategies across the WEF sectors. Finally, an economic appraisal of alternative adaptation options to solve water-energy trade-offs in the light of climate change has been undertaken. The more general results of the case study in Ethiopia at the national level regarding the quantification of trade-offs and synergies are:

- From a purely energy-cost and water-quantity point of view, the analysis showed that the projected rapid increase in electricity demand in Ethiopia up to 2050 can be met with large scale use of hydropower without compromising the increased domestic water use or irrigation water demand expansion. These results are irrespective of possible negative hydrological impacts as a result of climate change induced decreased precipitation nation-wide. These results, however, are based merely on economic and hydrological factors and do not taken into account environmental, geopolitical and social factors that may induce the Ethiopian government to reduce the investments in hydropower development.
- The Tiam model calculation resulted in an increase in biomass demand in Ethiopia from 1.1 EJ in 2010 to 1.9 EJ in 2050. Based on assumptions about the annual production of Eucalyptus, wood density of Eucalyptus and conversion factor to convert to kg biomass it was determined that, assuming the forest area does not change, it would require 156% of the existing forest area to meet biomass demand in 2050. The amount of water required to produce the required amount of biomass is estimated to be $6.21\ 10^{10}\ m^3$ water in 2050, which corresponds to approximately 500 mm per year over the forest area.
- As a separate analysis, the cost-effectiveness of a reduction in distribution losses of urban water supply has been assessed. This adaptation measure is expected to affect the water balance in the agricultural and/or domestic water sector and will reduce annual hydropower vulnerability because of increased water availability. The NPV calculations done for the hydro and public water sector separately showed negative results if the discount rate is less than 2.7 % but is positive if NPV is calculated for both sectors simultaneously (multi-sector perspective). These results show that the business case of an adaptation measure can be positively influenced by taken into account the effects related to other sectors.

The more specific results include:

Water and food security

The growth in population and food demand is expected to drive an increase in agricultural land. A way to limit the expansion of agricultural land would be to increase the yield per crop. However, this would require the intensive use of pesticides and fertilizers which in turn would impact water quality through water run-off and nitrate pollution. Potential nexus solutions that could trigger improvements in food production include:

- Conservation and climate smart agriculture techniques;
- Improvements in soil nutrient levels, seed quality and /or irrigation systems.

- Agricultural and water rights reforms that create the right incentives for farmers to invest in more efficient irrigation systems.

Water and energy security

Hydropower requires large volumes of water to be stored. Water consumed through reservoir evaporation cannot be used by other users. Another link between these two sectors concerns the biomass use in households which is the largest driver of deforestation, which can lead to deterioration in groundwater recharge capacity and water quality. Potential nexus solutions that affect both sectors positively include:

- Development of most abundantly available renewable energy technologies such as solar, wind and geothermal
- Accelerating the introduction of more efficient cook stoves, especially among rural households
- Facilitating a switch from firewood to more convenient fuels such as LPG, electricity and kerosene.

Energy and food security

Several interactions exist between energy and food security. Land used for biofuel production cannot be used for agricultural purposes and vice versa. Dung used as fuel for cooking cannot be used for fertilization and increased crop production to supply the agro processing industry will require increased amounts of energy. Potential nexus solutions that could create synergies between the energy and food sectors:

- Introduction of afforestation and deforestation policies
- Solar powered water pumping for irrigation.

The road ahead: methodological findings, recommendations and research gaps

The current study provides the conceptual framework that can be used to analyse and evaluate the trade-offs and synergies between the water, energy and food sectors. Effective implementation of nexus solutions requires however collaboration between the three sectors and further research is needed to identify the conditions that facilitate cooperation and collaboration across these sectors. The research should inform what institutional structures should be built to support the adoption of technical nexus solutions.

Based on the findings of the present study it is recommended to conduct further research on how to define the nexus in a specific context: under what conditions do critical links exist beyond the WEF nexus. An obvious example is climate change which is interlinked to the WEF sectors through changing weather patterns but other sectors such as sustainable production and consumption may also affect the WEF sectors. This broadening of the nexus scope is especially relevant for the SDG framework which comprises 17 goals and 169 related targets that have many interactions.

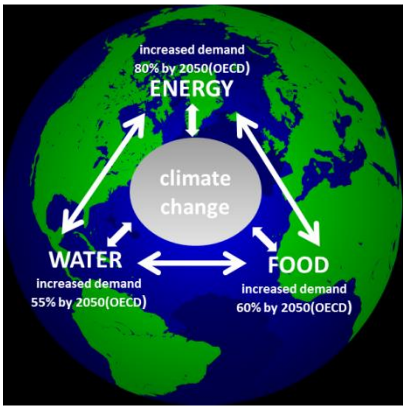
The modeling package comprising the Ribasim/Tiam/water-limited yield models was used to analyse quantitatively the interactions between the water, energy and food sectors. For the present study these three models were soft-linked; output from one model was manually entered as input for the other models. If these models could be physically integrated so that intervention in one sector is automatically taken into account in the other sectors, it would enable the identification of optimal solutions across the three sectors simultaneously.

1. Introduction

In Chapter 1 an explanation is given of why the Water- Energy-Food (WEF) Nexus approach is essential for achieving long-term water, energy and food supply security. This chapter elaborates on the role the WEF Nexus can play in the UN 2030 development agenda and outlines the elements relevant for this report of the Paris agreement adopted at the UN FCCC Conference held in Paris in December 2015 (COP2015).

1.1 The need to take a Water-Energy-Food nexus approach

According to UN DESA[1] the current world population of 7.3 billion is projected to reach 8.5 billion by 2030, 9.7 billion in 2050 and 11.2 billion in 2100. Most of this increase is expected to be concentrated in nine countries: India, Nigeria, Pakistan, the Democratic Republic of Congo, Ethiopia, the United Republic of Tanzania, the United States of America, Indonesia and Uganda. Based on these population trends and on rapid urbanization and rising living standards, it is estimated that by 2050 global energy demand will increase by 80%, water demand by 55% and food demand by 60%[2].These trends are placing increasingly competitive demands upon finite natural resources for agriculture, energy and water. The effects of climate change pose an additional challenge, as heavy flooding in coastal areas and severe droughts in more arid regions could further exacerbate this competition and seriously impede economic growth.



Thus far, energy, food and water challenges have mainly been addressed within the sectors concerned. This has resulted in policies and interventions that focus primarily on individual sectors, rather than considering the broader cross-sectoral impact. This lack of coordination, dialogue and collaboration among sectors can significantly affect the efficiency and effectiveness of policies and may also prevent appropriate measures from being taken. So there is an urgent need to address these challenges simultaneously and develop an integrated approach. Balancing the trade-offs between these sectors will be essential if we are to achieve sustainable development and ensure water, energy and food security by maximising the potential synergies and efficient solutions.

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[1] UN DESA: World Population Prospects, the 2015 Revision.

[2] OECD Environmental Outlook to 2050: The Consequences of Inaction-Key facts and figures.

This growing need for integrated resources management thinking is what triggered the development of the Water-Energy-Food (WEF) Nexus concept which stems from system analysis and is centred around the many links that exist between the water, energy and food sectors. Water, for example, is used in agricultural production processes and for cooling the waste heat from power plants; energy is used for irrigation (pumping water), food production processes and power in agricultural machinery and tractors; and palm oil is used for cooking and is a key ingredient in food production, but it is also used to produce biofuel. Taking into account these links while designing policies to ensure long term water-food-energy supply security could result in more development using less natural resources.

The WEF Nexus concept gained considerable momentum at the Water, Energy and Food Security Nexus – Solutions for the Green Economy conference which took place in Bonn in November 2011 .Since then, a considerable amount of research has been conducted on the conceptualisation of the nexus and significant progress has been achieved, as evidenced by the research results presented at the two-day Understanding the Water-Energy-Food Nexus and its implications for Governance conference held in Osnabruck in June 2016. However, the research focus so far has mainly been on understanding and improving the conceptual framework of the nexus and much less on the quantification of the trade-offs and potential nexus synergies.

The Dutch Climate Solutions(DCS) research programme combines the expertise of research institutes from the water sector (Deltares), the food sector (Wageningen University) and the energy sector (ECN) and is therefore well positioned to research the WEF Nexus and to contribute to the debate on long-term water, food and energy supply security challenges. Furthermore, the DCS research institutes have at their disposal a unique set of modelling tools that describe mathematically the interdependencies between the WEF sectors, enabling them to assess the impact of demographic and economic developments and extreme weather conditions on the demand and supply of the WEF resources.

This report aims to make the complexity of the WEF Nexus more broadly known and understandable by quantifying the availability of resources, the trade-offs and the potential synergies using a concrete case study in Ethiopia, one of the countries in Africa where anticipated rapid economic and population growth is expected to lead to severe WEF resources challenges in the coming decades. Building on the conceptual framework resulting from system analysis, the abovementioned set of modelling tools has been used to assess the WEF trade offs in the year 2050 at national level, also taking into account the impact of extreme weather conditions due to the changing climate.

The quantitative analysis for Ethiopia presented in this report provides an important illustration of how a nexus approach is needed to reduce the conflicts arising from rapidly growing demand for resources. This requires that compartmentalised thinking, known as a silo mentality, be replaced by an integrated resources management approach. However, in order to bring about this paradigm shift we must also look at the institutional setting to ensure that information sharing and collaboration across the sectors is facilitated and that nexus perspectives are integrated into policies and strategies. The WEF Nexus can be understood as a governance system of institutions, policies, and actors around the issues of water, energy, and food security. Lack of awareness of the nexus interconnections, lack of coordination between the fragmented (and sometimes competing) institutions and lack of implementation of nexus strategies are often seen as more serious barriers than lack of innovative technology solutions.

The overall objective of the research presented in this report is to develop a conceptual and modelling framework to analyse the challenges in ensuring long-term water-energy-food supply security and to test this framework by applying it to the concrete case study of Ethiopia. The specific aims are to:

- Identify the links between the water, energy, forestry and food sectors.
- Analyse the long-term availability of resources and trade-offs between the energy, forestry, food security and water sectors at a national level.
- Formulate strategies that address the growing demand for resources simultaneously and take into account the impact of climate change on these sectors.
- Support the Dutch government in formulating climate-smart solutions that address the three sectors simultaneously.
- Assess the role of institutions and of learning and capacity-building in such an approach.
- Identify the business opportunities for the Dutch companies offering Climate Smart Solutions created by the mainstreaming of the nexus approach.

The scope of the research comprises the following elements:

- Climate change is not addressed as a separate economic issue, but as a cross-cutting issue that puts additional pressure on other sectors.
- Mitigation and adaptation strategies are considered to be relevant for the following sectors: water, food security, energy and climate change.
- The focus is on a quantitative analysis using a set of water, energy and agricultural computer models that describe the interconnections between these sectors.
- Elaboration of the WEF Nexus in relation to the Sustainable Development Goals(SDGs).

1.2 How does the WEF Nexus relate to the Sustainable Development Goals?

The main focus of the present research is on how to achieve an optimal use of water, energy and food resources to ensure water, energy and food security. Nevertheless it should be emphasized that to achieve the broader objective of sustainable development, other aspects such as poverty, land use, equity, gender, environment and health are equally important. The extent to which these other aspects should/can be incorporated in the WEF Nexus depends on the specific context that is being analysed.

In 2015, a consensus was reached by the 193 UN Member States on the development agenda for the period up to 2030[3]. The new agenda builds on the success of the Millennium Development Goals (MDGs) and includes a set of 17 Sustainable Development Goals (SDGs) to end poverty and hunger and tackle climate change by 2030. Similarly to the MDGs, for each SDG a set of concrete targets has been set to allow quantitative monitoring of the progress towards the goals.

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[3] Transforming Our World: The 2030 Agenda for Sustainable Development

There are numerous interconnections between the SDGs and the 169 related targets and the risk is that meeting these goals individually may be achieved at the cost of other goals and targets at different levels of governance. Achieving sustainable development by 2030 will be a daunting task given these inherent inter-sectoral tensions. Additionally, climate change is expected to result in a higher frequency of extreme events, intensifying these tensions and the uncertainties regarding the availability of the resources. Therefore achieving the SDGs is far more complex than solving infrastructure investment gaps – as it was perceived for the MDGs – and requires the recognition of the inherent trade-offs as well as potential synergies between the sectors.

The challenge is to identify – from among these many interactions – those links that are critical in the sense that they significantly influence the behaviour of the system. Taking these critical links into account helps to reduce the trade-offs between the SDGs, to avoid possible rebound effects and to identify potential leverage points to gain synergies.

The WEF Nexus is a part of the broader SDG development framework and basically covers only 3 out of the 17 SDGs[4]. A review of the SDG targets conducted by ICSU-ISSU suggests links between the nexus goals 2,6 and 7 and most of the other 14 SDGs. Based on the qualitative description of the linkages between the SDG targets presented in the review, the SDGs that are most likely to have the strongest links with the WEF, and thus affect the WEF system, are depicted in the following figure.

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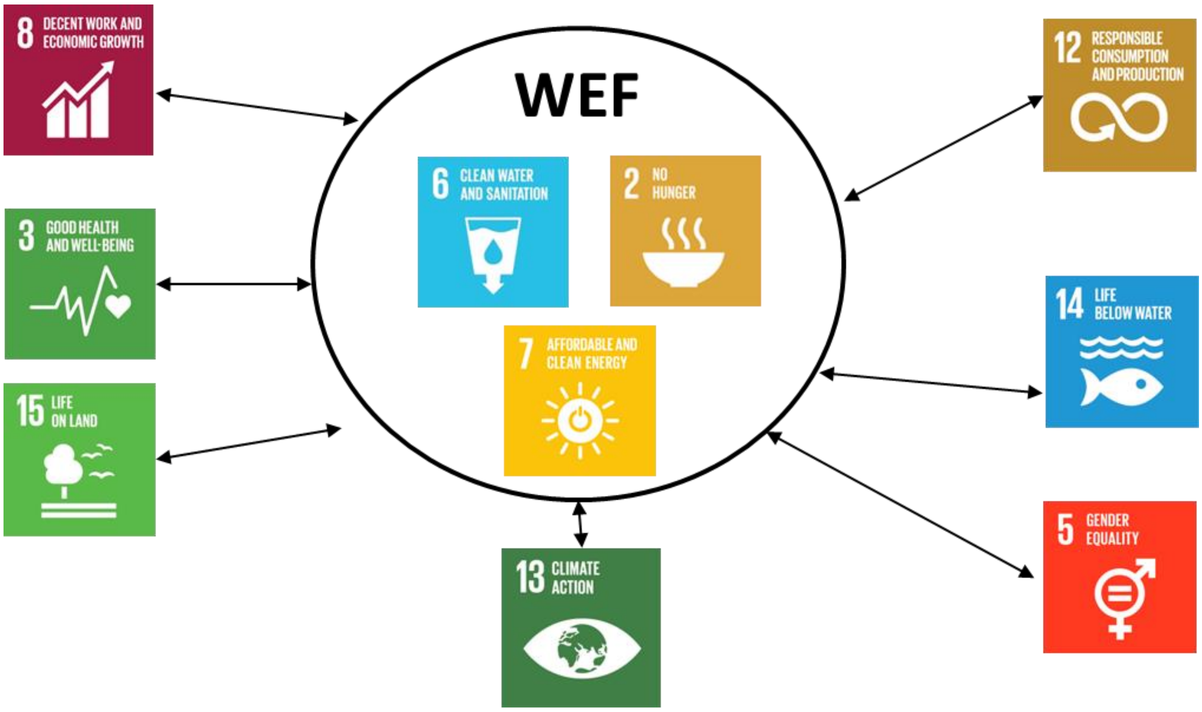
[4] Other SDG's such as number 15 and 8 are partially covered in our analysis due to the important impacts 2,6 and 7 have on them and/or due to the specific national priorities of the country being analysed, which are taken as point of departure for our WEF analysis.



1.3 The Paris agreement as the way forward

The Paris Agreement is a landmark in the climate negotiations. The key outcomes of COP21 are captured in Article 2 of the decision (see Box).

> Article 2
>
> This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
>
> (a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
>
> (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
>
> (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate- resilient development.
>
> Source: FCCC/CP/2015/L.9/Rev.1

The three elements of the decision are clear; however the manner in which parties will take up the challenges is less well defined. It is open to the countries to define efforts and collaborative initiatives. The voluntary nature and transparent character of the agreement is perhaps exactly what is needed to move forward as it provides an open field in which parties can learn and exchange ideas and technologies.

For mitigation, the low carbon development pathways are defined in the nationally determined contributions (NDCs). Besides the mitigation aims, the NDCs also include the activities that will be implemented at national level to achieve these aims. The process includes regular reporting on emissions and progress in implementing and achieving the NDCs.

For adaptation, the link to the sustainable development goals is obvious. Aligning the adaptation and development processes makes sense so parties are encouraged to shape national adaptation planning by jointly engaging in planning processes and the implementation of actions. Each party should submit and periodically update an adaptation communication, which may include its priorities, implementation and support needs, plans and actions.

Financing is a critical element of the agreement; this is particularly true for developing countries. Developed country parties will provide transparent and consistent information on support for developing country parties. Besides finance, capacity-building to plan and implement activities is particularly important for the least developed countries.

While all the ingredients are there, it is important that the momentum created during the Paris meeting should not be lost. So far fewer than 20 countries have ratified the agreement and the goal to hold the global temperature increase well below 2°C is not supported by the NDCs/INDCs. Financing pledges have been made and coordination mechanisms are being put in place. Capacity-building, exchanging methods, technologies and success stories are all needed to move the agreement forward.

Much of the follow-up will depend on available finance and examples on how to shape low-carbon and resilient development. There is already a great deal of knowledge and experience available to achieve the mitigation goals. National adaptation planning is emerging but needs examples and capacity-building activities to make this work. In this report we will reflect on the NDC submitted by Ethiopia and the adaptation plans it has prepared to see how a nexus approach can be used to assist in defining low-carbon and resilient development while reaching the sustainable development goals for the nation.

1.4 Reading guide

Given the purpose of this research which is to develop an analytical and modelling approach that allows for the quantification of trade-offs between the water, energy and food nexus at different scales; and create the required system understanding of the nexus to guide the generation of alternative Climate Smart Solutions and Strategies the report has been organized into five chapters.

In Chapter 1 an explanation is given of why the Water- Energy-Food(WEF) Nexus approach is essential for achieving long-term water, energy and food supply security. This chapter elaborates on the role the WEF Nexus can play in the UN 2030 development agenda and outlines the elements relevant for this report of the Paris agreement adopted at the UN FCCC Conference held in Paris in December 2015 (COP2015).

Chapter 2 provides an overview of the rapidly growing literature on the WEF Nexus and reflects on the state-of the art in this field. This review includes the barriers to the nexus implementation, key nexus principles and main criticism on the nexus thinking.

Chapter 3 introduces the conceptual and methodological framework developed to identify the interdependencies between the Water, Energy, Food (WEF) sectors and enable the management of this complexity. This framework draws on joint expertise of the DCS consortium partners representing the nexus sectors: ECN (energy), Wageningen UR (food and land) and Deltares (water) and considers four main steps: 1) Defining the problem, 2) Forecasting and management of climate uncertainty, 3) Analysis of trade-offs and synergies: identifying the critical links and 4) Formulating climate smart strategies: making use of leverage points and synergies.

In Chapter 4 this framework is applied to Ethiopia. Firstly, the key development challenges faced by Ethiopia are assessed and translated into important current and future intersectoral claims; including the analysis of the impact of Climate Change in these claims. Departing from the key intersectoral claims identified a more detailed analysis of trade-offs is realized. This includes the quantification of these trade-offs making use of Ribasim/Tiam/Water-limited crop models to evaluate long- term integrated demand and supply strategies across the WEF sectors. Based on the specific trade-offs and dilemmas identified for Ethiopia, potential points of leverage and synergies that should be taken into consideration in the formulation of Climate Smart Strategies are explored. To finalized the economic appraisal of alternative adaptation options to solve water-energy trade-offs in the face of Climate Change is presented.

To finalize in chapter 5 main findings, conclusions and recommendations regarding the further development of the nexus approach are presented.

2. Literature reviews of the WEF Nexus

This chapter provides a brief overview of the rapidly growing literature on the WEF Nexus and the progress achieved for the main research themes in this field. It explores the barriers to the nexus implementation and the additional principles for the nexus approach that are mentioned in the literature. Finally, the main criticism on the nexus thinking expressed in several publications is presented.

2.1 A historical overview of thinking about the WEF Nexus

The nexus approach was introduced as a new concept in the development discourse in 2008. The World Economic Forum embraced the concept and argued that there are important links between water, food, energy and climate change. It has since published several books and articles on the issue, with many detailed figures about current and future use of resources and challenges to be faced (for example The World Economic Forum Water Initiative, 2011).

In November 2011, as a specific contribution to the UN Conference on Sustainable Development "Rio2012", the German Government organised the Bonn2011 Conference “The Water, Energy and Food Security Nexus – Solutions for the Green Economy”. This conference was attended by more than 550 people representing diverse stakeholder groups and created the momentum for researching integrated approaches to address the supply security challenges of the water, energy and food sectors. In the background paper(Hoff, 2011) for this conference a nexus approach is defined as:

“an approach that integrates management and governance across sectors and scales. A nexus approach can also support the transition to a Green Economy, which aims, among other things, at resource use efficiency and greater policy coherence.”

Guiding principles advocated by Hoff (2011) for the nexus approach include:

- Investing to sustain ecosystem services. Such services are “the contribution of ecosystems to human well-being”, with particular importance for livelihoods of the poor and include food, feed, biofuels, wood, fibre. Other services include carbon sequestration and climate and water regulation.
- Creating more with less. There is a need for increased sectoral resource and overall resource efficiency. Reducing wastage along the production and supply chain – for developing countries especially on-farm and in transport and processing – is an issue where there is much to win.

- Accelerating access, integrating the poorest. There is considerable overlap between the 1.1 billion poor people without adequate access to water, the (close to) 1 billion who are undernourished, and the 1.5 billion who are without access to electricity. Synergies can be built and positive feedbacks generated across the three nexus sectors.

Hoff (2011) identifies a number of areas of opportunity for improving water, energy and food security through a nexus approach:

1. Increasing resource productivity (e.g. rainwater harvesting, desalination based on renewable energy, photovoltaic water pumps, second or third generation biofuels).
2. Using waste as a resource in multi-use systems (in multi-use systems , wastes, residues and by-products can be turned into resources).
3. Stimulating development through economic incentives (investment, for example, in research and development and reduction in perverse subsidies).
4. Governance, institutions and policy coherence (for example, learning platforms for social innovation, more participation in planning and decision-making).
5. Benefiting from productive ecosystems (for example, maintaining and restoring ecosystems, improved management and investment in (restoration of) natural capital, well managed agriculture ('agro-ecosystems')).
6. Integrated poverty alleviation and green growth (for example landscape management).
7. Capacity building and awareness raising. Capacity building and social learning can help to deal with the increasing complexity of cross-sectoral approaches and it can help to level the playing field among the nexus partners.

This typology of measures identified by Hoff (2011) aligns with the typology of leverage points or points of power to change the problematic behaviour of a system introduced proposed by Meadows (2007) and explained in greater detail in Chapters 3 and 4.

In FAO (2014) the context in which nexus thinking is emerging, is described as an ever increasing competition for natural resources by different sectors. In that context, the WEF Nexus has emerged as a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals. The aim of the nexus approach is to better understand and systematically analyse the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales. This can help us to identify and manage trade-offs and to build synergies through our responses, allowing for more integrated and cost-effective planning, decision-making, implementation, monitoring and evaluation. It is important to note that there are different conceptualisations of the nexus that vary in their scope, objectives and understanding of drivers. Several concepts, frameworks and methodologies have looked at the interconnections between water, energy and food, but also land and soil, minerals, and ecosystems.

The Water, Energy and Food Security Nexus – Solutions for the Green Economy conference in Bonn triggered a great deal of research on the WEF Nexus which can be divided into the following broad research themes:

I. Nexus interdependencies and integrated nexus modelling
II. Role of the nexus in the implementation of the SDGs
III. Policy Coherence and nexus governance.

The progress achieved on these topics since the Bonn conference was presented at the Scientific Forum "Understanding the Water-Energy-Food Nexus and its Implications for Governance" held in Osnabrück, Germany, in June 2016. The main conclusions for the three research themes drawn from the Forum were:

I. Detailed models exist and are used for developing and analysing water, energy and food policies. The main challenge and research focus now is to integrate these models to be better able to answer questions about the WEF Nexus. Models can serve a range of purposes and must be judged in the light of their intended purpose: 1) general understanding; or 2) policy formulation; or 3) detailed implementation. Important to note here is that many of the system changes are triggered by social behaviour which is not captured by the models and therefore other methods such as system dynamics should be used to complement the modelling analysis.

II. In order to achieve the SDG targets it is important to identify and quantify the ''critical'' links - those links that really affect the system - that exist between the 17 SDGs. This is necessary to address the trade-offs between the SDGs simultaneously and to avoid a situation in which one goal is achieved at the expense of another (the rebound effect). Evidence-based nexus research helps to better identify co-benefits that may motivate cooperation and thus improve policy coherence among the three sectors. Several methods can be used to identify these critical links: systems analysis (simple method based on expert judgment and not reproducible); cross-impact analysis (expert judgement assigns score to link to create a cross-impact matrix) and integrated modelling (reproducible but requires a great deal more resources). The current research focuses on the systems analysis and impact matrix to reduce the huge number of links to the ones that are really critical in a particular context and then to analyse those in detail with the integrated modelling approach. Other relevant questions that need to be researched are: 1) does the WEF Nexus capture all the links that are key for achieving the SDGs or does it miss the link with sectors such as land, health, industry, gender, poverty, climate change? and 2) Does the WEF Nexus focus more on optimizing resource use rather than on incorporating stakeholder perceptions?

III. The lack of policy coherence rather than lack of technical solutions is often mentioned as the main barrier to nexus-efficient solutions. Especially at the local level, integrated modelling is less useful because the models do not incorporate social and local knowledge and therefore often are perceived with scepticism. A participatory approach that focuses on involving all key stakeholders, identifying their interests and addressing the lack of awareness on nexus interconnections seems more appropriate for identifying and implementing nexus-driven solutions.

2.2 Criticism on the nexus thinking

Nexus thinking has now been in use for several years and it is being questioned on several issues. The main points of criticism expressed by Allouche et al. (2015) are listed below:

Is the nexus approach really something new?

There are already other approaches which try to integrate different disciplines and approaches, for example Integrated Water Resources Management. What might be new, is that the nexus tries to integrate different policy sectors, and it encourages business involvement. It could also be a multi-centric concept that treats the different sectors – water, energy, food and climate security – as equally important. A multi-centric approach is certainly desirable, but it is not new and it is extremely difficult to achieve. Integrated Water Resource Management came out of the water sector, the Landscape approach came out of the forest and biodiversity sector, and the nexus approach most of all resounds in the water sector. All aim to achieve integration, but each starts in its own sector (which is as such quite understandable). FAO (2014) also stresses the point that the nexus approach considers the different dimensions of water, energy and food equally and recognizes the interdependencies of different resource uses to develop sustainably.

Is the basic problem, the 'scarcity of resources' not a political issue which cannot be solved in a technological or managerial way?
Nexus policy documents tend to provide a narrative to manage economic structures through technological solutions, rather than questioning the inequalities (of access to resources) in the system. The crucial importance of political and power issues is also well-known within Multi-Stakeholder Processes and Partnerships for example for promoting changes in an economic sub-sector (forests, livestock raising etc.). Such MSP processes were sometimes initially seen as an 'easy' solution to all problems. To put it simply: let people from different stakeholder groups talk long enough and an acceptable solution will be the result. However, differences in knowledge and power between stakeholders and groups of stakeholders play a significant role and may result in powerful groups dictating a solution, or keeping others away from the negotiation table. There may be situations where powerful groups prefer to not participate at all in a negotiation process. Also differences between sectors (water, food, energy, climate change) in economic weight and power can play an important role.

Is the nexus approach not too optimistic about investment, innovation and ingenuity?
Key to the idea of nexus is 'efficiency' of resource use. But the logic of optimisation has limits. It treats the trade-offs between human needs for water, energy and food as a perfect equilibrium model, in which resource allocation can be decided. This can encourage the commodification of resources, downplaying environmental externalities, such as biodiversity and climate change, as well as poverty alleviation needs, ignoring day-to-day realities, local priorities and needs. Social dimensions of resource (nexus) links remain thinly described and under-theorised. While there may be biophysical limits, the nexus promotors follow an optimistic view where these limits can be overcome through investment, innovation and ingenuity, driven by even more sophisticated technologies.

Are we not hiding the bigger debate?
The current concept is being approached as an almost magical solution that quickly solves long-term fundamental and structural issue. This technical veil masks a bigger debate, which lies around resource inequality and access that contribute to social instability.

Is integration of the food, water, energy and climate change sectors really possible?
Given that food, water and energy sectors often exist in silos, the idea of integration may be challenging to put into practice. The different governing regimes of water, land and energy will make nexus governance even more difficult.

2.3 Barriers to implementing the nexus approach

Vanloqueren & Baret (2009) made a comparison of research efforts for genetic engineering and agroecology and tried to answer the question why genetic engineering received considerably more research funds than the much more holistic concept of agroecology. Based on that comparison the following factors might explain the difficulty in integrating the sectors in a nexus approach:

1. Until now *public policies* have not been focusing much on the integration of sectors. Governmental bureaucracies also are organised according to sectors (water, food, nature, forests, energy, climate change, etc.), often in different ministries.

2. In recent years private sector participation in the delivery of public services has become a much more important goal. This can be seen in the promotion of the use of Public *Private Partnerships* and other innovative contracting approaches. While these structures may be viable for so called club goods, it should be noted that there are limits and challenges to the application of these hybrid public-private governance structures for the delivery of purely public goods and services. Two key challenges are the possibility to effectively transfer public sector to the private sector and effective performance measurement. Given the conflict of interests natural to the principal (public authority) and the agent (private company delivery the service) ; these two factors mentioned above are necessary conditions to achieve the benefits of PPP's while limiting the negative effects of opportunistic behaviour. A poor implementation of PPP's for the delivery of public goods may result in a improper focus on development of new commercialised products to the detriment of externalities (not accounted for in the contract) such an increase in emissions or reduction of biodiversity.

3. It is only recently that some private sector parties (particularly multinational companies) see the need to apply a more holistic approach in their business model and started to deal in their business practices with issues related to the nexus between food, water, energy and climate change. The visible and increasing effects of climate change in water availability is making more companies aware of their vulnerabilities and the fact that nature is their real license to operate; encouraging them to look for more effective risk mitigation measures and to invest in so-called Beyond the Fence measures at watershed level.

4. In the media, holistic approaches like a nexus approach do not receive much attention. It may be too complex and it is easier to tell the public about a single issue or sector. NGOs that perform lobby and advocacy activities also have to obey to the law that you should not make things too complex in your communication and campaigns.

5. *Private sector* research is not focusing on integrated approaches like the nexus. The general perception is that it would be difficult to make the results of such a research profitable for a company, either because is beyond their direct area of influence and/or because to realize such collective investments would make them incur in significant transaction costs .

6. *Publicly funded research* has traditionally been organised sector-specifically. Integrated research and research on integrated systems do not have a high reputation. In sector-specific approaches, scientists share common cultures, languages, methods and techniques. By contrast, an integrated approach like nexus requires a greater integration of agronomical, ecological, social, economic, water, climate and energy dimensions. It is also one step further away from research at laboratory scale which seems the most esteemed type of research (being closer to the ideals of positivism and reductionism). It is also a step away from measurable innovations per sector towards variables that are much more complex to measure, like sustainability and externalities. Innovations in the complex field of nexus takes years before producing any publishable results and fewer papers means a lower ranking of the scientist in question. However research is of the utmost importance for explaining the success of sectors. For example, modern agricultural

systems rely on a wide scientific basis, an enormous accumulation of the results of investments in agricultural research during the last 160 years (Pardey and Beintema in Vanloqueren& Baret, 2009).

7. *Each sector has its own network.* In many sectors, stakeholders from policy, research and civil society meet frequently to discuss current issues. The food, water, energy sectors each has their own networks. These different networks are barely connected. To make it even more complex, 'Climate Change' often has its own network, while it is not an economic sector.

The identified barriers are significant and there are no easy solutions to overcome them. Important regulatory and political reforms and their proper enforcement (which will require significant institutional development) combined with the introduction of new production and economic models are key to create new formal and informal incentives for public sector, the private sector and civil society to act. Additionally a new way of working that encourages coordination, creates trust and enables effective communication between the energy-water-food and energy sectors and all stakeholders (public, private and civil society) herein active, would be of significant value to remove some of these barriers.

2.4 Possible additional principles for the nexus approach

To address the criticisms mentioned above, the following additional principles have been suggested to strengthen the nexus approach:

1. The need for participatory planning process: there is a need for more emphasis on decentralised and democratised decision-making as the source of solutions, as well as the source of understanding the challenges faced (Allouche et. Al (2015).
2. The need to pay special attention to livelihoods: to adequately incorporate sustainable livelihoods perspectives Biggs et al. (2015) the concept of Environmental Livelihood Security (ELS) was developed by Biggs et al.(2015) which encompasses, among other things, a matrix with four aspects: livelihoods, water, energy and food. They identified fundamental internal and external (influencing) factors present between these four aspects.
3. Involvement of businesses in nexus approaches.
4. The need to pay attention to adaptive capacity of institutions.

3. Conceptual and methodological framework for the WEF Nexus

A majority of governments around the world in developed and developing countries have separate agencies to oversee water, energy, and agricultural food production. These separate agencies set policies, develop plans and plan investments for each sector separately. They favour 'siloed' approaches that represent the traditional way of governing, where one resource is controlled and managed by a simple industry, often under specific government legislation.

In this chapter a conceptual and methodological framework is presented that aims to identify the interdependencies between the Water, Energy, Food (WEF) sectors and is able to handle the complexity of it. This framework draws on joint expertise of the DCS consortium partners representing the nexus sectors: ECN (energy), Wageningen UR (food and land) and Deltares (water). Each of them bring along expertise and practical lessons from projects conducted around the world in the following areas: hydrology, integrated water resources management, energy system analysis and energy technologies, agriculture and landscape management.

3.1 Conceptual framework

In order to build a conceptual framework which is shared among the relevant disciplines we have made use of System Analysis and Group Model Building techniques. Two group model building techniques have been organized. The first session aimed to achieve a clear interdisciplinary framing of the problem and focused on the linkages between SDG's and the nexus. The second session aimed at supporting the choice of case study area in Ethiopia and focused more in depth on agriculture and landscape management as the impact of on-going projects of Wageningen UR in Ethiopia was reviewed. The results of the Group Model Building session 1 are presented in Appendix F. A limitation on this process has been the fact that we have limited participation to the three DCS consortium partners without directly involving relevant stakeholders. This limitation will be dealt with in the second phase of this research, by involving all relevant stakeholders of the Ethiopian case study on the application of the framework making use of participatory modelling techniques.

For a systematic process of discovery and in depth analysis of the interdependencies between the sectors (trade-offs and synergies) within the nexus, we have made use of System Dynamics techniques complemented with an in depth literature review of the interdependencies between the sectors. Needless to say, in the application of System Analysis and System Dynamics[5] techniques the emphasis has been on discovery of key interdependencies – as the nexus concept requires it- and not aiming at a Holistic approach.

Systems thinking and System Analysis support the drafting of conceptual models that portray interconnections, cause- effect relationships, feedbacks and time delays between and within dynamic systems. These interconnections are represented by so-called Causal Loop Diagrams (CLD's). Once these conceptual model structures have been drafted; System Dynamics can be used to understand the behaviour of these complex systems over time. These conceptual model structures could be taken a step further and converted into dynamic numeric models in a computer environment.

Departing from this conceptual framework we will follow a methodological approach for the case study which consists of the following main steps:

1. Defining the problem
2. Forecasting and management of climate uncertainty
3. Analysis of Trade-offs and Synergies: identification of critical links and variables and quantification of trade-offs
4. Formulating Climate Smart Strategies: making use of leverage points and synergies.

Furthermore, a quantification of the trade-offs has been made by softly linking existing modelling tools -TIAM-ECN and RIBASIM- for water-energy interdependencies and complementing this analysis with excel calculations for biomass energy production in terms of land and water requirements.

Before introducing each of the steps it is important to explain the conceptual framework of the water-food-energy nexus. Our framework is depicted schematically as a system diagram, see Figure 1 and Figure 2.

A system is the part of reality that is being studied for the solution of a given problem. Two key steps for system specification are (Thissen and Walker 2013, p. 264):

- *Step 1: Which part of reality should be focused upon? Which actors and issues?*
- *Step 2: Which factors are relevant?*

The objectives of building a system diagram (Thissen and Walker 2013, p. 264) and its key elements are:

- Define system boundaries, what will be included and what will not

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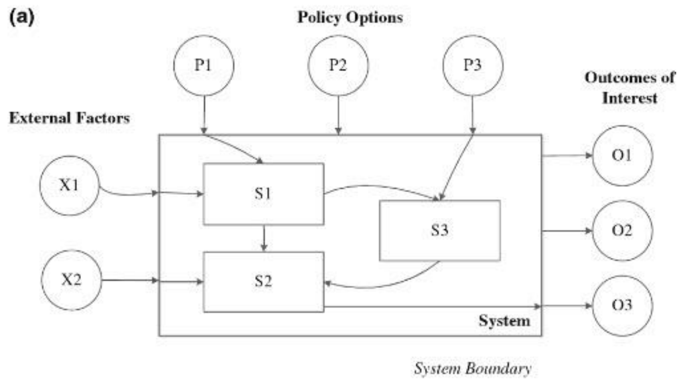
[5] System dynamics is based on systems thinking, which focuses on the system structure and offers a deeper insight into problems. The root causes of problems and therefore a sustainable solution for them are not always easy to identify due to the interactions and time delays that occur in a system (Assaraf and Orion, 2005; Gharajedaghi, 2011; Lewis, 1998; Zoller, 1990). Systems thinking offers a deeper insight into problems. It focuses on the system structure and the system behaviour produced by the structure (Senge, 1997). System dynamics (SD) is a modelling and simulation approach using systems thinking (Assaraf and Orion, 2005; Forrester, 1994). It is particularly powerful for the study of the nexus as it enables us to (a) capture the interconnections among different components (sub-sectors) within the (nexus) system, (b) identify stock and flow relationships, (c) recognise delays and their impacts on performance patterns, (d) simulate the structure of the system, and (e) explain the behaviour that the system produces (Draper, 1993; Forrester, 1994; Frank, 2000; Sterman, 2000; Sweeney and Sterman, 2000) and (f) last but not least, combine hard and soft variables. **Causal loop diagrams** (CLDs) and **stock flow diagrams** (SFDs) are the two basic tools used in model formulation.

- Define system structure and interdependencies
- Identify key *outcomes of interest*, the indicators that help us evaluate if a system is performing well or not, which are related to the objectives of the problem owner and that will be used as *criteria* for policy evaluation
- Identify alternative policy options, *instruments* or measures for problem solution
- Identify relevant contextual factors, so-called *external factors*. These are elements that cannot be influenced by the problem owner(s).

A system diagram in very simple terms can be depicted as follows:

Accordingly the key building blocks of a system diagram for policy analysis can be categorized as follow: *External factors* and *Instruments* serve as input; this input is then transformed by a process and results in output, which is to be measured in terms of *outcomes of interests.*

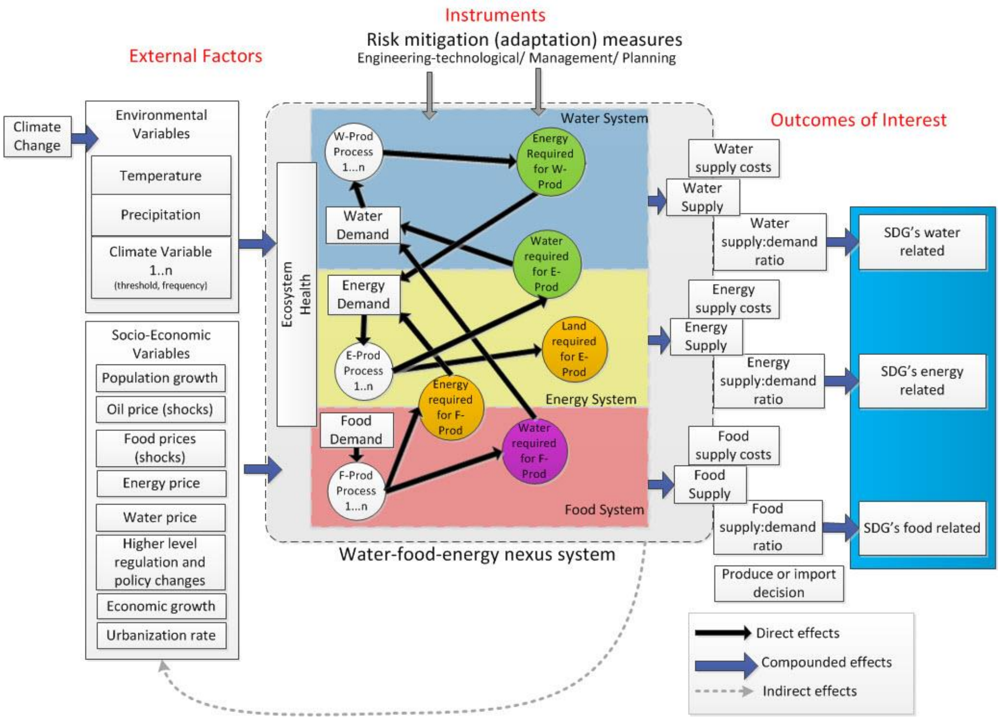
Figure 1 System Diagram structure (Source: Thissen & Walker 2013, p.265).



The process is captured by the main rectangle where system borders are represented by solid or dashed lines. In these process subsystems (represented by rectangles) and their interdependencies (represented by arrows linking factors) result in a number of mechanisms that ultimately drive system behaviour and performance.

Figure 2 depicts the System Diagram of the water-food-energy nexus. In this section the key building blocks and assumptions of this diagram will be introduced. Section 4.1.5 will give a more in depth explanation of this diagram and its use in a System Analysis of the nexus.

Figure 2 System Diagram of the water-food-energy nexus



The System and its boundaries

The system and its boundaries are depicted on the main rectangle and represented by the dash lines. The nexus system comprises of three subsystems representing each sector. In each sector – represented by a primary colour- a number of production processes take place that: a) ensure the supply of the required yearly flows of water-energy and food by the population but that also pose a claim on the resources of other sector(s). These claims are represented by the circles at the right side of the subsystems and have been assigned secondary colours that reflect the two sectors involved. The claims embody key interdependencies and trade-offs in the nexus:

- Energy required for Water Production,
- Water required for Energy production,
- Land required for Energy Production, the production of biomass results in less available land for food production, therefore reducing the yearly food supply
- Energy required for Food Production and
- Water required for Food Production.

The larger these claims the larger the chances are that scarcity of stress is experienced by the sector, endangering the achievement of water, food and energy related Sustainable Development Goals.

Two important boundary conditions of our conceptual approach are:

a) Climate Change and Ecosystem health[6] are considered cross-cutting issues affecting all three subsectors through a variety of variables. Although climate change is depicted as an external factors, as the feedback arrow indicates, the way the system perform in the long

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[6] Ecosystem health may be defined as the capacity for maintaining biological and social organization, on the one hand, and the ability to achieve reasonable and sustainable human goals on the other (Rapport et al., 2001).

term and via indirect effects will affect also the values of external factors. Ecosystem Health is depicted as a factor having an impact across all three sectors and affecting the production capacity of each of them.

b) To combat climate change adaptation and mitigation measures are needed and therefore our analysis of the nexus takes these measures as point of departure for the analysis of interdependencies (e.g. a larger share of renewable energy sources).

Outcomes of interest – the gap to be solved
The outcomes of interest depicted at the extreme right side of the diagram refer to the output variables and represent the interests and the criteria by which the problem owner and relevant stakeholders judge the performance of the system and monitor the impact of measures on the problem. A problem in Systems Analysis is defined as the gap between the desired situation or value of a criteria and the reality or current value.

As depicted in the system diagram, the main objective of the water-food-energy nexus system is to ensure sustainable economic development and the achievement of the SDG's 6 (6.1, 6.3, 6.4 and 6.6) and 11 (11.5) for water and water related disasters, 7 for energy and 2, 12 and 15 for food and land management. Accordingly the Outcomes of Interest and/or Key Performance Indicators of the Nexus System correspond to the relevant SDG indicators. Three examples would be: a. Access to (safe and affordable) drinking water (% of total population), b. Access to modern energy (% of population) and c) Percentage of children (<5 years) stunted or malnourished.

External Factors
External factors have been divided in two main groups: environmental and socio-economic variable. While environmental variables affect more directly the production processes, socio-economic variables are key drivers for demand of energy, water and food. Important environmental variables are precipitation and temperature, both affected by Climate Change. Meanwhile key socio-economic variables are population and its growth, prices shocks of oil, food and energy; national regulation and policy frameworks as well as country preferences for producing versus importing energy, food and/or water.

As indicated above, in energy policy analysis import/export is not seen as exogenous, price shocks are not taken into account because they are only temporarily (typically 6-12 months) and policy frameworks are endogenous.

Instruments or policy options
Last but not least, in reaction to the problem faced a problem owner can influence the system by implementing a variety of Climate Smart Solutions and Climate Smart Strategies as combinations hereof. These solutions could vary from engineering and technological measures up to regulatory and planning approaches. These different options are reviewed and their potential to solve the trade-offs or to create additional synergies within the nexus is analysed.

3.2 Methodological approach: steps to follow

As mentioned above, our methodological approach consists of four main steps: 1) Problem definition, 2) Adding Climate (and policy) uncertainty, 3) Analysis of Trade-offs and Synergies, and 4) Formulating climate smart strategies. All these analytical steps need to be accompanied by a well-designed process to ensure active engagement of key stakeholders and significant representation and ownership of the agreements by the authorities of the three sectors: water, food and energy. Collaborative modelling techniques have proved effective as stakeholder management technique especially for decision making process when the problem at hand has a complex nature.

As it will be illustrated making use of the System Diagram presented in Figure 2 in each step different elements of the water-food-energy system are analysed. Each step can be supported by different methodologies.

The four steps suggested by our approach are:

Step 1: Defining the problem
This step includes a number of sub steps:

(a) Identification of key development challenges: by making a quantitative estimation of the most important gaps in terms of the Sustainable Development Goals and other national policy priorities. Analytically we suggest to make a rough quantitative estimation of current performance of the system and the challenge ahead; making use of the SDG's suggested indicators or proxies and the baseline information for water stress, energy balance and food scarcity. A guide to realize this process is presented in Appendix A, where the proxies per SDG's and the most important data sources are presented. The result of this first step is then the list of the most important Outcomes of Interest for the country or region applying the framework.

(b) Stakeholder analysis: based on the interests of the stakeholders identified as crucial the Outcomes of Interest listed should be revised.

(c) Analysis of cross-sectoral claims: Establishing most important interdependencies between sectors, by quantifying and prioritizing in order of magnitude the five cross-sectorial claims mentioned above; making use of Appendix B. Once the key two or three intersectoral claims have been identified, the production processes of the sector making the claim in another sector should be analysed aiming at discovering the most resource intensive ones. A guide to realize this process is presented is also presented in Appendix B, where the Production processes of each sectors requiring input from other sectors are presented.

(d) Draft a first problem definition (what is the problem about and how bad is it?) where the key development challenges and cross-sector dependencies that could result in unintended negative side effects of preferred or traditional measures are acknowledged.

In this step it is decided upon which part of reality should the further analysis be focused? And which actors and issues? Based on the findings of a, b and c choose the key interdependencies and processes per sector to be analysed in depth and then proceed to step 2 - evaluate the impact of Climate Change on these factors and step 3- analysis of trade-offs and synergies between the sectors.

In terms of process this first step should be accompanied by a collaborative modelling exercise including the key decision makers of the three sectors and other relevant stakeholders to be selected depending on the scale on which the analysis is being made. The results from the quantitative analysis should be seen simply as one of the many possible hypotheses, and only aiming at ensuring a facilitation of the discussions with stakeholders informed enough so as to ensure concrete new insights about nexus are shared.

Step 2: Forecasting and Management of (Climate) Uncertainty
Analyse the impact of Climate Change and other future scenarios – defined as combinations of a wide range of values for environmental and socio-economic factors – on a) claims made from one sector to another, b) production processes per sector and as result on c)the achievement of SDG's. This analysis could be done in a quantitative way or in a qualitative way.

In order to keep the analysis easier to grasp, in the application of this framework to Ethiopia we have opted for a focus on this step on the uncertainties introduced by climate change, while taking into consideration the changes in socio-economic variables introduced by the policy agenda of a country in the analysis of current and future intersectoral claims (step 1). A more complete analysis should also consider other socio-economic scenarios other than the ones considered in official documents.

Step 3: Analysis of trade-offs and synergies: identification of critical linkages and variables and quantification of trade-offs
Before the formulation and generation of solutions can start it is necessary to understanding the key mechanisms, virtuous and vicious cycles, drive explain the problematic behaviour of the system. A powerful method to do so is System Dynamics and the related Causal Loop Diagrams (CLDs) . By depicting the causal relationships between specific factors in the three sectors in a CLD and analysing it one can discover critical variables and points of leverage for the decision maker. It is important to mention that correlation is not causation and that therefore the use of statistical models in this step should be done with caution. Causation is the "story behind the model" (Thissen en Walker, 2013) which enables the discovery of **leverage points**.

Points of leverage are the factors within a complex system where a small shift can result in significant changes in system performance, they are the places to intervene in a system. These could be identified by analysing CLD's and finding out the factors that influence many other crucial factors simultaneously. If a quantitative System Dynamics model is used, these can be identified by making a sensitivity analysis and finding out the parameters that when varied 1o% produce a more than 10% change in the value of the outcomes of interest. However it should be noted that even more powerful leverage points than changes in specific parameters, may be identified when looking at other soft-variables that define the governance of water, food and energy resources. This will be explained and illustrated in greater detail in the following section.

Special attention should be paid to the identification of these points of leverage. As stated by Jay Forrester, the founding father of System Dynamics, complex systems are counterintuitive.

Leverage points are not intuitive. Or if they are, we intuitively use them backward and push them in the wrong direction, systematically worsening whatever problems we are trying to solve[7]*.*
*(*Meadows 2007*).*

As a result of Step 2 and 3 it is decided which factors and system mechanisms are relevant. These could be then quantified making use of a variety of simulation and/or optimization models. As sectoral models do not capture the implications of interventions in one sector for another sector; we recommend the creation of soft or hard linkages between these models to be able to quantify these trade-offs. As it will be shown in chapter 4, we have opted for soft-linkages between TIMES (TIAM-ECN) energy models, water balance models (RIBASIM) and excel calculations for the land and food sectors.

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[7] Leverage points: places to intervene in a System, available at: http://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

Step 4: Formulating Climate Smart Strategies: making use of leverage points and creating synergies

Once points of leverage for decision makers have been identified and the trade-offs and synergies between sectors are well understood, the process of formulation of measures or “Climate Smart Solutions” can start. Climate Smart Solutions are measures varying from engineering and technological measures up to regulatory and planning approaches that can effectively influence critical variables and make use of the system leverage points.

Climate Smart Solutions include a wide range of Smart Technological Solutions as well as Integrated Policy Solutions that are effective and efficient in affecting leverage points, in ensuring multiple SDG’s, minimizing conflicts and maximizing synergies across sectors and enhancing the potential for cooperation between and among all sectors.

In the following chapter all these steps are followed for the case of Ethiopia and in this way the use of the framework is illustrated.

4. Applying the framework to Ethiopia

In this chapter the conceptual framework presented in the previous chapter is applied to Ethiopia. Firstly, based on the methodological approached developed we assessed in depth the key development challenges of Ethiopia, its policy agenda and how this translate into important intersectoral claims now and in the future, as well as how these will be affected by Climate Change. Departing from the key claims identified we zoom and making use of the trade-offs - already identified through the literature review (Chapter 2) and summarized as a matrix (Annex C) and depicted as Causal Loop Diagrams (Annex D)- we analysed in depth critical linkages and interdependencies between the three sectors, the specific trade-offs and dilemmas faced by Ethiopia and potential points of leverage and synergies that should be taken into consideration in the formulation of Climate Smart Strategies.

Secondly Ribasim/Tiam/Water-limited crop model set was used to quantify the interactions between the sectors and to evaluate long- term integrated demand and supply strategies across the WEF sectors. Until the present study these sector models were used by the consortium partners to analyse sector specific strategies. In the present study these models have been soft linked to create a powerful model package that enables a detailed analysis of the consequences of policy measures taken in one sector on the other sectors.

Last but not least, an economic appraisal of alternative adaptation options to solve water-energy trade-offs in the face of Climate Change is undertaken.

4.1 Step 1: problem definition

4.1.1 Identification of key development challenges

This section aims to provide an overview of the critical development priorities of Ethiopia's and how they relate to the WEF nexus, from a national and global perspective. The national and global perspectives are represented by the national policy priorities and the SDG agenda respectively. By a) identifying Ethiopia development priorities and operationalizing them as quantitative gaps between their (SDG) targets and the current situation and analysing, and b) analysing the additional resource demands the achievement of these gaps simultaneously would generate; we generate understanding on future resource constraints to the equitable economic growth of Ethiopia and potential future conflicts in the use of their resources, and the trade-offs between different policy targets and agendas.

Setting out development priorities, their current status and the difference between both reveal future resource demand. Comparing this to the boundary conditions of the system, e.g. resource availability generates understanding on the criticality of certain objectives and potential conflicts.

Global policy agenda:
The Sustainable Development Goals

Table 1 below shows those SDG targets related to the WEF-nexus where Ethiopia shows the largest gaps. Table 1 is an excerpt from Appendix A, which contains a review of WEF-nexus related SDG variables based on the World Development Indicators (WDI) database[8].

A critical challenge for achieving sustainable development in Ethiopia is meeting the population's primary needs, symbolized by SDG targets 2.1 and 6.1, representing food and water security respectively. For target 2.1, eradication of undernourishment assumes sufficient access to food. Access to energy is also a crucial factor for economic development, embodied by SDG target 7.1. In this case a reliable and modern energy supply implies access to electricity.

For SDG target 15.1 concerning the sustainable management of Ecosystems, there does not seem to be a gap. However, given the expected economic development, population growth, reliance on wood fuel and the current downward trend in forest cover, forest conservation will be a challenge. Forest conservation is taken into account in to the WEF-nexus since it is assumed to influence sustainable provision of water, food and energy. Directly, forest cover can influence water supply and water quality, among other things (Neary et al., 2009).

Table 1 SDG targets, indicators and their status for Ethiopia

SDG target	SDG indicator (target)	Target versus Status Ethiopia	Gap
2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.1 Prevalence of undernourishment	Target: 0% 32% (WDI, 2015)	32%
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Percentage of population using safely managed drinking water services	Target: 100% Status: 57.3 % (WDI, 2015)	42.7%
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.1 Percentage of population with access to electricity.	Target: 100% 26.6% (WDI, 2012)	73.4%
15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.	15.1.1* Forest area as a percentage of total land area	Target: 20% (GTP II) 12.5 % (WDI, 2015), 13.4% (WDI, 2002), (14.9% (WDI, 1992)	7.5%

Given current development gaps in these areas, the indicators in Table 1 can be considered key outcomes of interest for the Ethiopian government.

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[8] https://data.worldbank.org/data-catalog/world-development-indicators

Climate agenda

The latest national policy document by the government of Ethiopia concerning the global climate agreements is the INDC (Federal Democratic Republic of Ethiopia, 2015) which was prepared for the 21stConference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) held in December 2015. The INDC is clear about the national mitigation objectives, which are to see a 64% reduction in greenhouse gas emissions from the BUA scenario by 2030. For adaptation initiatives, the reduction of the vulnerability of the population, the environment and the economy to the impacts of climate change are presented as key areas. In line with GTPII, actions are linked to sectors.

The mitigation target in the INDC is formulated as: "The emissions reduction, which constitutes a reduction of 255 MtCO$_2$e or 64% compared to 'business-as-usual' (BAU) emissions in 2030, includes 90 Mt CO$_2$e from agriculture; 130 Mt CO$_2$e from forestry; 20 Mt CO$_2$e from industry; 10 Mt CO$_2$e from transport; and 5 Mt CO$_2$e from buildings. This does not include the reduction of 19 Mt CO$_2$e in neighbouring countries due to the export of electric power to them from Ethiopia."

In 2010 livestock and deforestation/forest degradation were the main sources of greenhouse gases:

- Livestock emitted methane and nitrous oxide totalling 42% of the total.
- Deforestation and forest degradation due to cutting and burning fuel wood and due to logging contributed 37% of the total emissions.
- Emissions from electric power generation, transport, industry and building were each only 3% of the total.
- Crop cultivation contributed 9%.

In the same document, Ethiopia states as main goal for its adaptation activities: to increase resilience and reduce vulnerability of livelihoods and landscapes in three pillars: drought, floods and other cross-cutting interventions.

This INDC was based on the Climate Resilient Green Economy Vision and Strategy of Ethiopia (CRGE). The CRGE (FDRE, 2015) is Ethiopia's Strategy for addressing both climate change adaptation and mitigation objectives. Some priority initiatives under the CRGE include the use of more efficient stoves, increasing reforestation and an afforestation ambition beyond the earlier target of 7 million hectares with continued involvement of local communities.

The most important outcomes of interest concerning the climate agenda of Ethiopia are:

- Emissions (MtCO$_2$e) from Agriculture, Forestry and Industry: these are closely related to deforestation rate and livestock production.
- Vulnerability of livelihoods and landscapes (SDG 11.5: 5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations)

National policy priorities

In this section we review some important policy papers from Ethiopia, dealing with the sectors of agriculture, water and energy, and climate change.

The national planning commission finalized in 2016 the second Growth and Transformation Plan (GTPII) in which the successes of the first GTP will be taken forward. GTPII (FDRE, 2016) aims to contribute to achieving Ethiopia's vision:

"to become a country where democratic rule, good-governance and social justice reign upon the involvement and free will of its peoples, and once extricating itself from poverty to reach the level of a middle-income economy."

In this chapter we examine the WEF Nexus and identify possible bottlenecks or synergies that may strengthen the GTPII.
Ethiopia's ambition is to become a lower middle-income country by 2025. Strategic pillars introduced in GTP II are:

a) Sustaining the rapid, broad based and equitable economic growth and development witnessed during the last decade including GTP I;
b) Increase productive capacity and efficiency to reach the economy's productive possibility frontier through rapidly improving quality, productivity and competitiveness of productive sectors (agriculture and manufacturing industries);
c) Enhance the transformation of the domestic private sector to enable them become capable development force;
d) Build the capacity of the domestic construction industry, bridge critical infrastructure gaps with particular focus on ensuring quality provision of infrastructure services;
e) Proactively manage the on-going rapid urbanization to unlock its potential for sustained rapid growth and structural transformation of the economy;
f) Accelerate human development and technological capacity building and ensure its sustainability;
g) Continue to build democratic and developmental good governance through enhancing implementation capacity of public institution and actively engaging the citizens;
h) Promote women and youth empowerment, ensure their effective participation in the development and democratization process and enable them equitably benefit from the outcomes of development;
i) Building a climate resilient green economy.)

These pillars provide the basis and direction for integrated inclusive development. The implementation of GTP I and II is sectoral with agriculture (crop and livestock) as the main engine for economic growth. Energy is a key element in the national economic infrastructure and large scale investments in hydro and wind energy have been made over the last decade. Water is seen as important in the overall economic infrastructure of the country notably in the services (potable water supply) and agricultural (irrigation) sectors (FDRE, 2016).

IN GTP II Ethiopia's National Planning commission and Ministry of Finance & Economic development aim for economic growth by transitioning from an economy dominated by agriculture to a more diversified economy that can deliver (light-) manufactured goods with a higher added value. The envisioned transition can be linked to a traditional economic growth model[9], which describes different stages of economic growth, moving from a traditional subsistence-driven agricultural society to a mature economy based on domestic consumption of high-value consumer goods.

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[9] See stages of growth by Rostow (1990).

For an economy to ‘take off’ to maturity, the secondary sector (goods-producing) share of the economy needs to surpass the primary (agriculture) sector share (Rostow, 1990). Ethiopia aims to do this by developing a light-manufacturing sector that produces goods such as textile and garment, leather products, footwear, agro-processing, sugar and others. Agricultural output serves as input factor to these production processes and is therefore a driving force, as acknowledged by GTP II.

Another determinant of economic transitioning is through exporting additional production of consumer goods abroad, thereby earning foreign currency, which can be used for importing products and improving the balance of trade, leading to macroeconomic sustainability through an improved exchange rate among other things. For increasing agricultural and thereby manufacturing output, a reliable supply of energy and water is needed. Therefore, investments in irrigation and energy production capacity are carried out in Ethiopia.

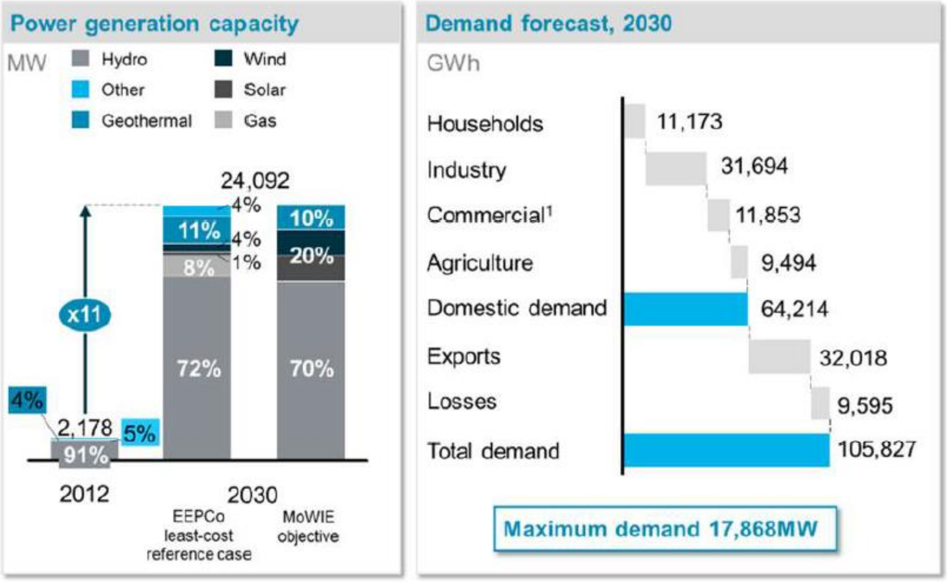
Other national development objectives related to water, energy and food supply are covered in Ethiopia’s Green Economy Climate Resilience Strategy: Water and Energy (FDRE, 2015). The Green Economy Climate-Resilience Strategy (CRGE is an integral part of the GTPII ambition to achieve development goals in a sustainable manner. Accordingly it describes the national targets for water and energy access, among other things. Key elements in this strategy are:

1. Improving crop and livestock production practices for higher food security and farmer income while reducing emissions
2. Protecting and re-establishing forests for their economic and ecosystem services, including as carbon stocks
3. Expanding electricity generation from renewable sources of energy for domestic and regional markets
4. Leapfrogging to modern and energy-efficient technologies in transport, industrial sectors, and buildings.

Building on the Climate Resilience Green Economy vision, the Climate Resilience strategy sets out the implementation priorities for the Ministry of Water, Irrigation and Energy, the Ministry of Agriculture and Natural resources and the Ministry of Environment and Forest.

Ethiopia’s current and planned power generation capacity is depicted in Figure 3 below. Currently, the country is mostly dependent upon hydropower for its power generation. Although hydropower would remain the predominant power source in 2030, the energy mix is planned to become more diversified in 2030. Peak domestic and foreign energy demand is estimated at 17,868MW.

Figure 3 Ethiopia's current and planned power generation capacity (FDRE, 2015)



1 Commercial figures include: commercial, street lighting and transport sectors
2 Other sources include Diesel, Biomass, Sugar and Energy from Waste

For an overview of the main policy objectives relevant for the WEF-system identified by Ethiopian policy see Table 2 below.

Table 2 National policy indicators, status and targets of Ethiopia

Indicator	Status	Target
Average real GDP growth per annum	10.1 % (2010-2015)	11% (2016 – 2020)
Major crops production	270 million quintal (2015)	406 million quintal (2020)
Area of land irrigated	2.3 million ha (2015)	4.1 million ha (2020)
Power generating capacity	4180 MW (2015)	24092MW (2030)
Potable water supply coverage	58% (2015)	85% (2020)
Forest coverage	15.5	20% (2020)

Accordingly from this analysis we can conclude that key outcomes of interest for the Ethiopian government, based on their policy priorities are:

- Light manufacturing output (contributes to SDG8.1 Economic growth)
- Export/import ratio (contributes to SDG8.1 Economic growth)
- % of population with access to WASH/potable water (SDG 6.1 and 6.2)
- % of population with access to electricity (SDG 7.1)
- Forest coverage (SDG 15.1)
- % of population undernourished (SDG 2.1).

As it can be seen above, four of these six outcomes of interest relate to SDG goals.

4.1.2 Stakeholder Analysis

In this step we analyse the position of key stakeholders and based on these results the list of outcomes of interest depicted in section 4.1.1 Identification of key development challenges; needs to be revised.

Table 3 Main stakeholders and their interests

Stakeholder (national level)	Role/ responsibility /mandate	Strategic plan for which it is responsible	Outcomes of interest (criteria)
National planning commission / Ministry of Finance & Economic Development	- Set overall long term perspective and five years medium term growth targets[10] - Provide general guidance for planning and development priorities - Approve the plan - Review the periodic evaluation results	Growth and Transformation Plan II	- GDP growth (SDG 8.1) - Macroeconomic imbalances - Agricultural output (SDG 2.3) - Manufacturing output
Ministry of Water, Irrigation and Energy (MoWIE)	- Promote the development of water resource and electricity - Cause the carrying out of study, design and construction works to promote the expansion of medium and large irrigation dams - Support the expansion of potable water supply coverage; follow up and coordinate the implementation of projects financed by foreign assistance and loans; - Promote the growth and expansion of the country's supply of electric energy[11]	Ethiopia's Climate-Resilient Green Economy Climate Resilience Strategy: Water and Energy One WASH Cookstove program	- Energy production capacity (SDG 7.1) - Hectares of irrigated land - Water supply - People with access to WASH (SDG 6.1)
Ministry of Environment and Forest (MEF)	- the implementation of the CRGE strategy, and overall environmental and forest management in the country[12]	Ethiopia's Climate Resilient Green Economy Climate Resilience Strategy; agriculture and forestry	- Ecosystem health (SDG 15.1) - Hectares of forests (SDG 15.1) - Biomass use (related to SDG 7.1 and 7.2)
Ministry of Health	To promote health and wellbeing of Ethiopians through providing and regulating a comprehensive package of promotive, preventive, curative and rehabilitative health services of the highest possible quality in an equitable manner.	One WASH national program	- Population health (SDG 3)
Ministry of Industry	Promote and expand the development of industry by creating conducive enabling environment for the development of investment and technological capacity of the industry sector by rendering efficient support and services to the development investor.	'Industrial park development Document'	- Manufacturing output

Table 3 above describes the main stakeholders active in Ethiopia's policy setting arena, each with their corresponding responsibility, outcomes of interest and strategic plan which outlines their priorities. Given the priorities of all actors, several possible conflicts of interest can arise in the future, dependent on the available resource base. The Ministry of Finance and Economic Development and the Ministry of Industry aspire economic growth based on agricultural output in

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[10] http://www.unosd.org/content/documents/14293-03%20Ethiopia%20New%20Institutional%20Framework.pdf

[11] http://www.mowie.gov.et/mandateandresponsibility

[12] https://www.forestcarbonpartnership.org/sites/fcp/files/2015/April/Ethiopia_Semi-Annual%20Report_FCPF_31515_Final.pdf

combination with light-manufacturing industry. Furthermore, generating a significant part of economic growth through export markets can partially contribute to the objective of improving macroeconomic stability.

Increasing agricultural output destined for light-manufacturing will require additional land, water and energy. The Ministry of Water and Energy aims to increase supply of water and energy supply, through irrigation and (renewable) energy production projects, for the varied purposes, including WASH services and agriculture. The Ministry of Health is mainly concerned with a healthy population, reflected by access to WASH and nutrition, among other things. The Ministry of Environment and Forestry focuses on environmental quality and forest cover.

With several actors simultaneously requiring water, food and energy for fulfilling their objectives, the extent of additional water and energy supply vis-à-vis increased water and energy demand stemming from demographic and economic growth will be fundamental to potential conflict. In case of conflict, the balance between developing water and energy resources for domestic, subsistence-oriented- versus international, high-value purposes will steer the direction of national development, pro-poor or pro-growth. However, sufficient institutional capacity with respect to income redistribution can share the benefits of economic development over multiple actors. Nonetheless, given the potential future challenges, domestic food and water security might be necessary regardless of any income distribution.

The Ministry of WIE targets increasing water and energy availability by the planning set out in the Climate Resilient Green Economy strategy, setting targets for irrigation and energy production development. Besides that, the National Cookstove program should reduce carbon emissions from deforestation and forest degradation and ensuring large scale adoption of clean cooking technology by supporting the dissemination and adoption of improved cook stoves in Ethiopia.

The Ministry of Health, in collaboration with other ministries, has set out the One WASH National Program. This program aims to “improve the health and well-being of communities in rural and urban areas by increasing equitable and sustainable access to water supply and sanitation and the adoption of good hygiene practices. It combines a comprehensive range of water, sanitation and hygiene interventions that include capital investments to extend first-time access to water and sanitation as well as investments focused on developing the enabling environment, building capacity, ensuring the sustainability of service delivery, and behavioural change” (IRC, website).

Ethopia’s aims for becoming an African leader in light-manufacturing are supported by the development of industrial parks, led by the Ministry of Industry, Ethiopian Investment Commission and the Industrial Parks Development Corporation.

The influence of various actors and policy instruments at their disposal will be illustrated in the WEF-system diagram in Figure 8 , section 4.1.5.

As it can be seen in the list of outcomes of interest per stakeholder, most of these outcomes correspond to the SDG targets and/or the targets specified in key policy agendas. Based on this analysis the list of outcomes of interest needs to incorporate the following:

- GDP Growth (SDG 8): dependent on other outcomes already identified such as (light) manufacturing output.
- Population Health (SDG 3) – this is of course very much dependent on SDG2.1 and other concerning food security.

Nexus governance

From this brief overview of policy documents and allocation of responsibilities the following conclusions can be drawn as to Ethiopia and the nexus in agriculture, water, energy and climate change:

1. There has been considerable thinking and strategy development on climate change adaptation in the sectors under review: agriculture, water and energy. Priorities have been formulated based on previously developed criteria and involving various Ethiopian experts. For implementation, refining of ideas and quantification will have to take place. Part of the activities can be taken up within existing programmes, but extensive additional funding is necessary. This seems to be a considerable risk. Maybe more consideration is needed on the question of how to involve the private sector and private-sector investment in climate-change adaptation.
2. In Ethiopia the water and energy sectors are managed by the same ministry. There is one climate-resilience strategy for the two sectors. From a nexus perspective these are positive aspects because apparently the two sectors are already seen as linked. This has led, for example, to the notion that the country should not only focus on hydropower for its energy needs, since variability in water availability is a very serious issue.
3. When it comes to the relations with the agricultural sector, it should be noted that the water sector is already considering the water needs to a great extent. This is not surprising, since in many countries agriculture is the largest consumer of water and traditionally the water sector takes agricultural needs into account.
4. The relation between energy and agriculture seems to be less defined. To what extent could lack of energy in the rural areas hamper agricultural development (e.g. energy for irrigation, energy for storage and processing of agricultural products and transport)?
5. When we look at agriculture in a broader sense and thus include forestry, there is on the one hand the need to increase agricultural production and on the other hand the need to intensify forestry production (fuel wood). A tension between these two objectives is possible given constraints in land availability.

4.1.3 Analysis of current and future cross-sectoral claims

The objective of this analysis is to identify the most important interdependencies between sectors, by quantifying and prioritizing in order of magnitude the five cross-sectorial claims; making use of Appendix B. For the key claims identified, the production processes of the sector making the claim to another sector is analysed with the aim to identify the the most resource intensive production processes within that sector and guide in this way the further in depth analysis of trade-offs. A guide to realize this process is presented in Appendix B, where the Production processes of each sectors requiring input from other sectors are presented.

Based on our analysis the main current and future inter-sectoral resource claims, in decreasing order of magnitude, are as follows:

1. Water required for agricultural production
2. Water required for energy production
3. Energy required for agricultural production
4. Land required for energy production
5. Energy required for water production

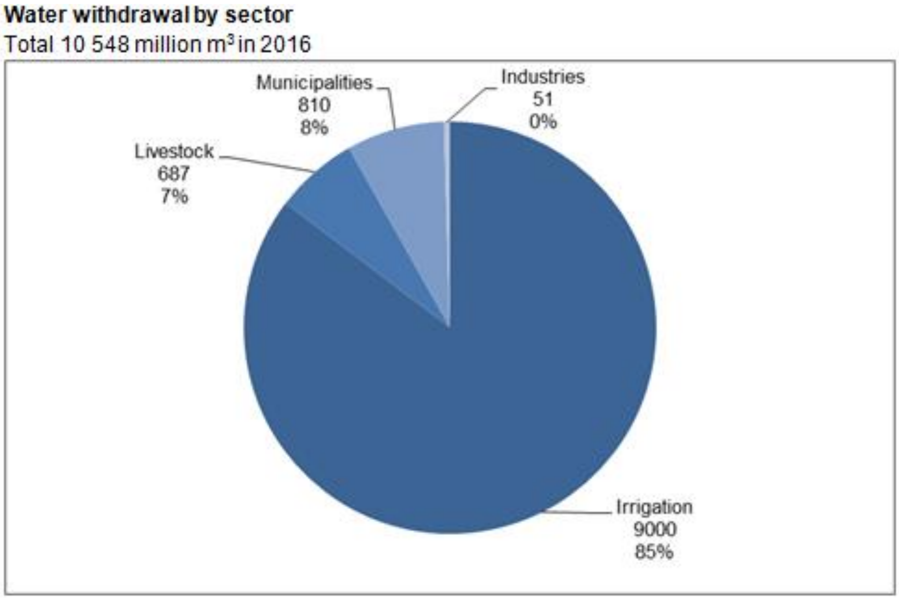
The rationale for the order of the claims and their magnitude, as well as the analysis of production process for the water and energy sectors that requires most resources from the agricultural and energy production sectors is presented below.

Water required for agricultural production

Currently, 38.5% of Ethiopia's GDP is realised through agriculture and allied sectors. In 2020 this share is aimed to be 33.5 (FDRE, 2014)). GTP II states that "agriculture will remain the main driver of the rapid and inclusive economic growth and development. It is also expected to be the main source of growth for the modern productive sectors. Therefore, besides promoting the productivity and quality of staple food crops production, special attention will also be given to high value crops, industrial inputs and export commodities. To this end irrigation based agriculture, horticulture, fruits and vegetables, livestock and fisheries development will be promoted" (p. 78).

Ethiopia aims to achieve this agricultural development and growth by increasing major crops production by around 50% and nearly doubling the area of land developed with modern small scale irrigation schemes, by 2020 (FDRE, 2016). Water for irrigation is the dominant share of water withdrawals, shown by Figure 4 below which illustrates the water distribution in Ethiopia with respect to withdrawals per sector. Extrapolating this figure to the future taking into account increased demand, water for agriculture is assumed to remain the dominant inter-sectoral claim in the future.

Figure 4 Water withdrawal by sector, Ethiopia (Aquastat, 2016)



The prevalent crop portfolio will be altered due to a shift towards agricultural output destined for the manufacturing industry, which is further scrutinized in section 4.1.4. Additionally, meat consumption is expected to increase with economic development. For example, York and Gossard (2004) found that for African countries a $1,000 increase in per capita GDP equals an increase in 1.66 kg of meat per person per year. Meat is generally known for its large water footprint (Mekonnen & Hoekstra, 2012). Therefore, water required for agricultural production will likely further increase through livestock demand due to a change in dietary preferences.

According to Ethiopia's 'Agriculture and Forestry strategy' (2015) "Ethiopia has the largest livestock population in Africa mainly made up of cattle (53m), sheep (26m), goats (23m) and poultry (50m). Like agricultural cropping, livestock production is mainly based on traditional techniques, whether mixed farming or pastoralism. A large proportion of livestock holders own just a few animals". Total meat production is planned to increase from 1,3 million tonnes to 2,1 million tonnes in 2020 (FDRE, 2016).

Water required for energy production

In Ethiopia power generation capacity is expected to grow from 2,178MW in 2012 to 24,092MW in 2030. 70% of this growth will be driven by hydropower development (see figure 3 above). Therefore, the energy sector claim to the water sector is expected to grow substantially.

Another source of energy that consumes water is embodied by the use of biomass. In 2010, 89% of Ethiopia's total national energy consumption was based on biomass energy. Biomass energy is consumed for household energy purposes, e.g. cooking. It has been estimated that 81% and 11.5% of 16 million households cook with firewood and leaves/dung cakes respectively (Geissler et al., 2013).

Based on population growth estimates, absolute biomass energy consumption is expected to increase further. However, the claim on water resources resulting from biomass energy consumption depends on the type of biomass and its production method. Biomass energy can come from the natural stock of woody biomass, on-farm trees, crop residues or dung. For 2013, annual total sustainable natural woody biomass yield is estimated to be 49.7 million tons (air dried weight). Annual total on-farm yield is 110.2 million tons. Crop residues and dung deliver 22 and 32 million annual tons respectively.

Therefore, when the increase in biomass consumption relies on natural woody biomass the claim on water resources does not increase. In an extreme case, water and land resource availability could increase due to deforestation. Nevertheless, deforestation decreases ecosystem health and (ground) water retention capacity, negatively affecting water availability and quality (Neary et al., 2009).

Increased biomass energy use stemming from on-farm tree production will increase the claim of the energy sector on water resources. Additional crop residue and dung consumption will increase water consumption, albeit indirectly. Uncertainty about future biomass energy production methods inhibits a detailed estimation of this future claim on water resources. Nonetheless, extrapolating current biomass consumption based on population growth creates a substantial future claim, assuming a distribution of production methods similar to current biomass energy production.

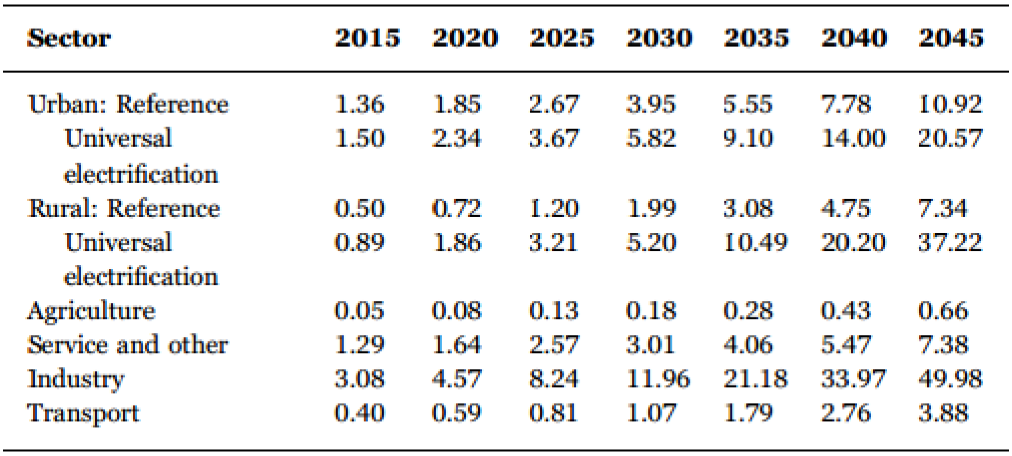
Energy required for agriculture

Making use of Appendix B, the table Food production – Energy demand we identify that within the agriculture sector, energy is needed for: a) food production harvesting, b) processing and/or packaging, c)transport, d)storage and cooling and e)cooking of food. Important energy claims for Ethiopia, especially in the future relate to processing and/or packaging; due to the growth of the agro-industry.

The surge in agricultural output will affect energy use of this sector, since additional output needs to be served by pumping systems, tractors, assembly lines etc. Moreover, energy consumption will increase due to Ethiopia's aspired increase in industrial processes that are linked to agricultural input such as textile manufacturing, leather production, agro-processing, sugar production and meat, milk and honey production (FDRE, 2016).

Table 4 below illustrates current and future electricity demand of Ethiopia's various sectors. The direct share of agriculture can be considered marginal. Nonetheless, around 25% of industrial electricity demand is assumed to stem from the agroindustry sector (GTP II). Since industrial electricity demand is the largest current and future consumer, 25% can be assumed to be a substantial claim on energy resources.

Table 4 Electricity demand in the reference and universal electrification scenarios (Twh), LEAP model results (Mondal et al., 2017)



Sector	2015	2020	2025	2030	2035	2040	2045
Urban: Reference	1.36	1.85	2.67	3.95	5.55	7.78	10.92
Universal electrification	1.50	2.34	3.67	5.82	9.10	14.00	20.57
Rural: Reference	0.50	0.72	1.20	1.99	3.08	4.75	7.34
Universal electrification	0.89	1.86	3.21	5.20	10.49	20.20	37.22
Agriculture	0.05	0.08	0.13	0.18	0.28	0.43	0.66
Service and other	1.29	1.64	2.57	3.01	4.06	5.47	7.38
Industry	3.08	4.57	8.24	11.96	21.18	33.97	49.98
Transport	0.40	0.59	0.81	1.07	1.79	2.76	3.88

Land required for energy production

As it can be seen in Appendix B, table Energy production- Food demand; the production of energy also poses a claim on food production directly or indirectly via: a) the use of food products such as corn for the generation of biofuel, b) the land claimed for biofuel crop production (or other energy generation processes) that is not available for food production, or c)land required for other energy generation installations such as wind and solar.

Error! Reference source not found. illustrates that 91% of Ethiopia's current electricity production originates from hydropower. As mentioned previously, 89% of Ethiopia's total national energy consumption is based on biomass energy.

As depicted by Figure 3 future electricity generation capacity is expected to experience an 11-fold growth path. Hydropower's claim on land resources is relatively small (from a KWh per m^2 perspective) compared to other energy sources, e.g. wind and solar power. With 70% of future capacity stemming from hydropower the total claim on land seems to be relatively modest. Nonetheless, the 20% wind and solar production capacity will require land availability.

The future claim of biomass energy on land resources depends on the production method, e.g. natural wood or on-farm trees. For example, an unsustainable yield of natural wood will generate land resource availability. On the other hand, additional on-farm tree production will require more land resources. Currently, no information on future biomass production methods has been acquired.

Energy required for water production

Currently, a large share of Ethiopia's drinking water needs is covered by groundwater supply. Around 70% of rural water supply comes from groundwater sources and ground water is also important for the large cities (Aquastat, 2018). Energy required for water production from groundwater is assumed to be relatively small due to the limited energy needs for groundwater extraction and purification compared to other methods such as reuse and reverse osmosis.

Since Ethiopia currently uses around 10% of renewable water resources (Aquastat, 2018), a large share of untapped resources remain. Therefore, additional water resource development can commence with cheaper, less energy-intensive methods, before it has to revert to more expensive, energy-intensive methods[13]

4.1.4 Main inter-sectoral claims

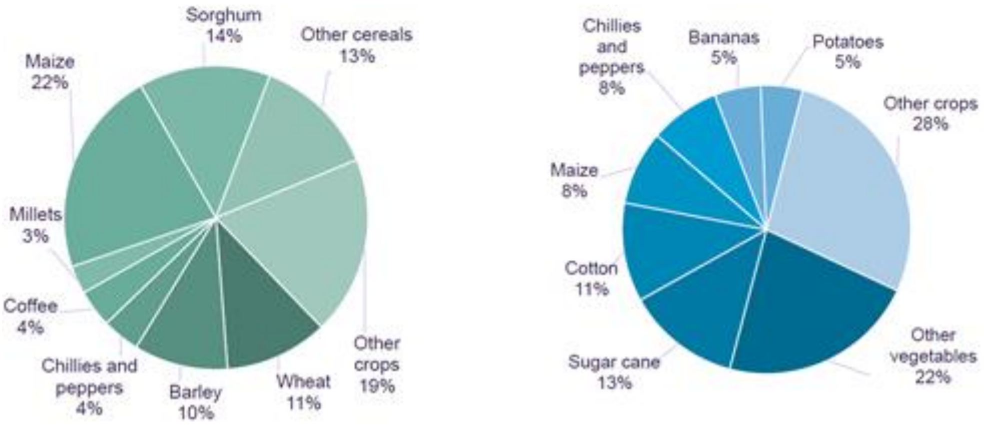
Based on our analysis it can be argued that the most important future inter-sectoral claims will be water required for agriculture and water required for energy, as they seem largest in magnitude and have multiple interdependencies with other sectors. The sections below will provide a more detailed analysis of these inter-sectoral claims.

Food production claims on water

Water demand of agriculture has been identified as the largest current and future demand source for water, fuelled by population and economic growth. By looking in Appendix B to the Table food production-water demand we observe that water in the agricultural sector may be required for a) Irrigation, b) fertilizers production, c) processing, d) water for animals and 5) water as habitat for fish. Based on our analysis we have identified a) water for irrigation and d) water for animals as important ones now and in the future. As Ethiopia advances in the development of their agro-industry also water for b) fertilizers production and c) processing will become more and more important.

The agricultural sector mainly consists of small-scale subsistence farmers using traditional farming techniques that are dependent on rain-fed water resources. 8 million households, 95% of the total cropped area and more than 90% of total agricultural output are currently represented by this type of farming (FDRE, 2014) Figure 5 below confirms that staple foods related to subsistence farming such as sorghum, barley and other cereals are typically rain-fed (green water). Crops with a higher value typically destined for manufacturing such as cotton and sugar cane are typically reliant on surface- and groundwater (blue water), as shown by Figure 5 as well.

Figure 5 Green (left) and blue (right) water use of per crop type (CWFP, 2016)



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[13] See for example Hellegers, Immerzeel & Droogers (2013)

Table 5 below shows planned crop output according to the GTP II. Regarding cereals, maize, teff barley and wheat are mentioned. Regarding pulse crops, chick peas, filed peas and haricot beans are mentioned. In relation to oil crops, linseed, Niger seed and sun flower are mentioned. The envisioned 50% increase in crop output by 2020 illustrates the expected surge in future water demand. This demand is met partially by an expected growth from 2.3 to 4.1 million hectares of the area of land equipped with modern small scale irrigation schemes by 2020. Additionally, the area of land developed with large and medium irrigation schemes is expected to grow from 0,65 to 0,95 million hectares by 2020.

Table 5 Planned crop output for Ethiopia 2015-2020 (FDRE, 2016)

Variable	Current (2015)	Future (2020)
Total major crop production	270.3 (mln qt)	406 (mln qt)
Total production of stalk cereals	115 (mln qt)	171.78 (mln qt)
Total production of non-stalk cereals	120.3 (mln qt)	184.22 (mln qt)
Total production of pulse crops	26.4 (mln qt)	38.75 (mln qt)
Total production of oil crops	7.5 (mln qt)	11.5 (mln qt)
Coffee production	420 (thousand tonnes)	1045 (thousand tonnes)

Exact data on the future composition of Ethiopia's crop portfolio including location-specific water needs is required in order to quantify future water demand. Nonetheless, the planned expansion of the agroindustry sector will result in a larger share for more high-value crops such as cotton, sesame and coffee compared to today. Gerbens-Leenes, Hoekstra & van der Meer (2009) show that staple foods such as wheat and potatoes typically require less water than high-value crops

Water demand from fertilizer production is expected to double by 2020, with the supply of chemical fertilizers increasing from 1.2 million to 2 million metric tonnes. Meat production has a similar projected growth trajectory, with total output rising from 1.3 to 2.1 million tonnes. Furthermore, the projected growth of the agroindustry (e.g. cotton, leather, tahin) will increase water requirements for processing.

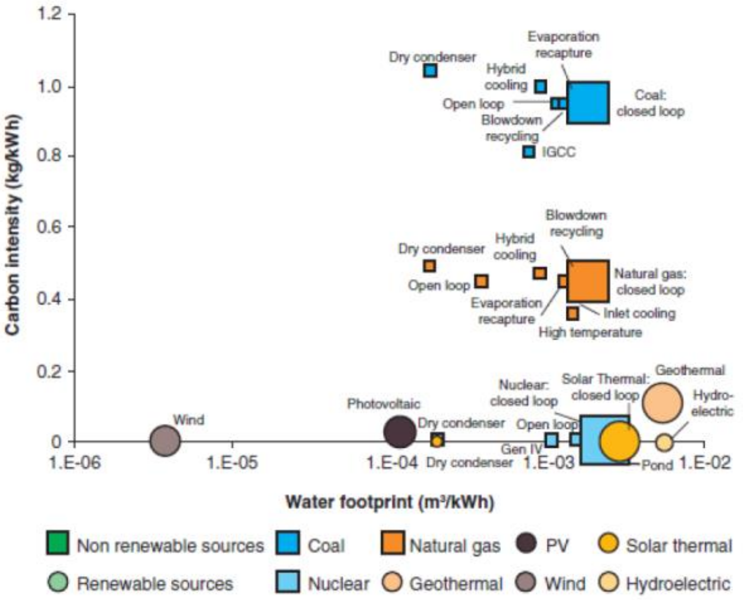
Energy production claims on water

Exactly quantifying energy-water trade-offs of different energy sources can be complex. Firstly, one has to determine the water requirements in terms of withdrawal, consumption and discharge. Withdrawal implies the amount of water abstracted from a water source. Consumption is the amount of water that is taken out of the water cycle, usually either as vapour or biomass. Discharge is the amount of water being returned to the water cycle, albeit in a different state (Rodriguez et al., 2013).

As shown in Appendix B many parts of the energy value chain consume water; on the table Energy production-Water demand, we observe that water in energy production is needed for a) processing and b) cooling; and different energy production methods that require water are: a) hydropower generation, b) energy plants (gas, coal, nuclear, etc) c) energy drilling and fracking, d)solar energy plants and e)biofuel production. As it is explained below, the production processes expected to require most water for energy production in Ethiopia are a) hydropower and e) biofuel production: biomass energy consumed by households, e.g. cooking.

Besides that, energy processing and production facilities' return flows often inflict water pollution. For example, hydropower production requires large amounts of water to be stored for energy generation and carbon capturing in energy production also requires water. Thermal power plants need large quantities for cooling purposes and developing energy in terms of extraction and refining requires water for coal, oil and gas. Furthermore, producing biofuels requires substantial amounts of water (Rodriguez et al., 2013).

Figure 6 Water footprint of energy sources (World Bank, 2016)



The power generating capacity of Ethiopia is aimed to expand from 4,180MW in 2014/15 to 17,208MW by 2019/20. As shown by Figure 6 above, the water footprint of this expansion is dependent on the distribution of production methods within this future portfolio. The future distribution of Ethiopia's electricity production portfolio is as follows; 13,817MW is planned to be generated from hydro-power, 1224MW from wind power, 300MW from solar power, 577MW from geothermal power, 509MW from reserve fuel (gas turbine), 50MW from wastes, 474MW from sugar and 257MW from biomass (FDRE, 2015).

A large share of the water use in the hydro-electricity sector is non-consumptive. However, the timing of water releases and affected water quality rates can impact other sectors. Moreover, consumption occurs in the form of reservoir evaporation and seepage, by amounts dependent upon site location and design. For example, a reservoir in an arid region might evaporate great amounts of water, whereas a run-of-the-river system stores and evaporates relatively small amounts of water.

Additionally, hydropower generation impacts the surrounding environment. An unbounded flowing river is converted into a reservoir, affecting water quality and ecology due to increased water temperatures and altered sediment and nutrient levels among other things. Therefore, the water footprint of hydro-electricity is among the largest in Figure 6 (Rodriguez et al., 2013).

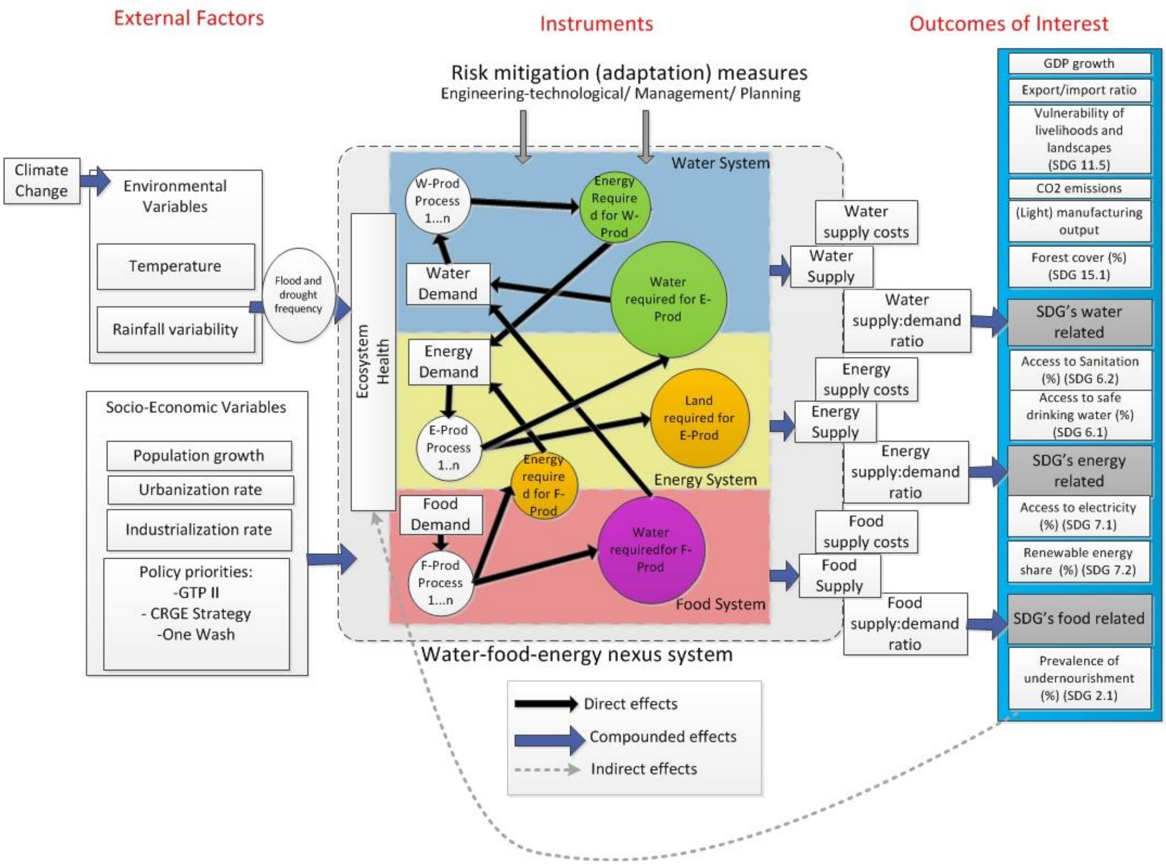
Ferroukhi et al. (2015) found that water use of wind is negligible, which is also confirmed by Figure 6 above. The water footprint of solar energy will be dependent on the exact production method, since some solar energy methods are more dependent on water than others, e.g. concentrated solar power compared to photovoltaic modules (Carter & Campbell, 2009).

Energy needs that are met by biomass, either for household or electricity generation purposes, will have significant implications for future water demand. Gerbens-Leenes, Hoekstra & van der Meer (2009) found that the water footprint of biomass is 70 to 400 times larger compared to other primary energy carriers except hydropower. Final water demand will depend on where biomass energy is sourced from. Sustainable yield from existing natural sources will not alter water demand, whereas additional on-farm biomass production, e.g. eucalyptus, will increase water demand.

4.1.5 System Diagram and problem definition

Based on all the analyses made before the overall WEF system diagram for Ethiopia is depicted in Figure 7. On the right side the key outcomes of interests for the actors reviewed in our analysis are presented; on the left side we see the external factors which cannot be directly influenced by the problem owner(s) and are the root of uncertainty about future developments. Finally in the middle top we see the instruments, measures or policies that could be adopted by the problem owners to affect the problematic behaviour of the current system and steer the WEF system to close the key development gaps identified. A more detailed analysis of the mechanisms driving system behaviour within the overall WEF nexus in Ethiopia is presented in Figure 8 . Appendix D contains more detailed Causal Loop Diagrams of specific key trade-offs and synergies, e.g. water for energy.

Figure 7 System diagram for the water-energy-nexus in Ethiopia



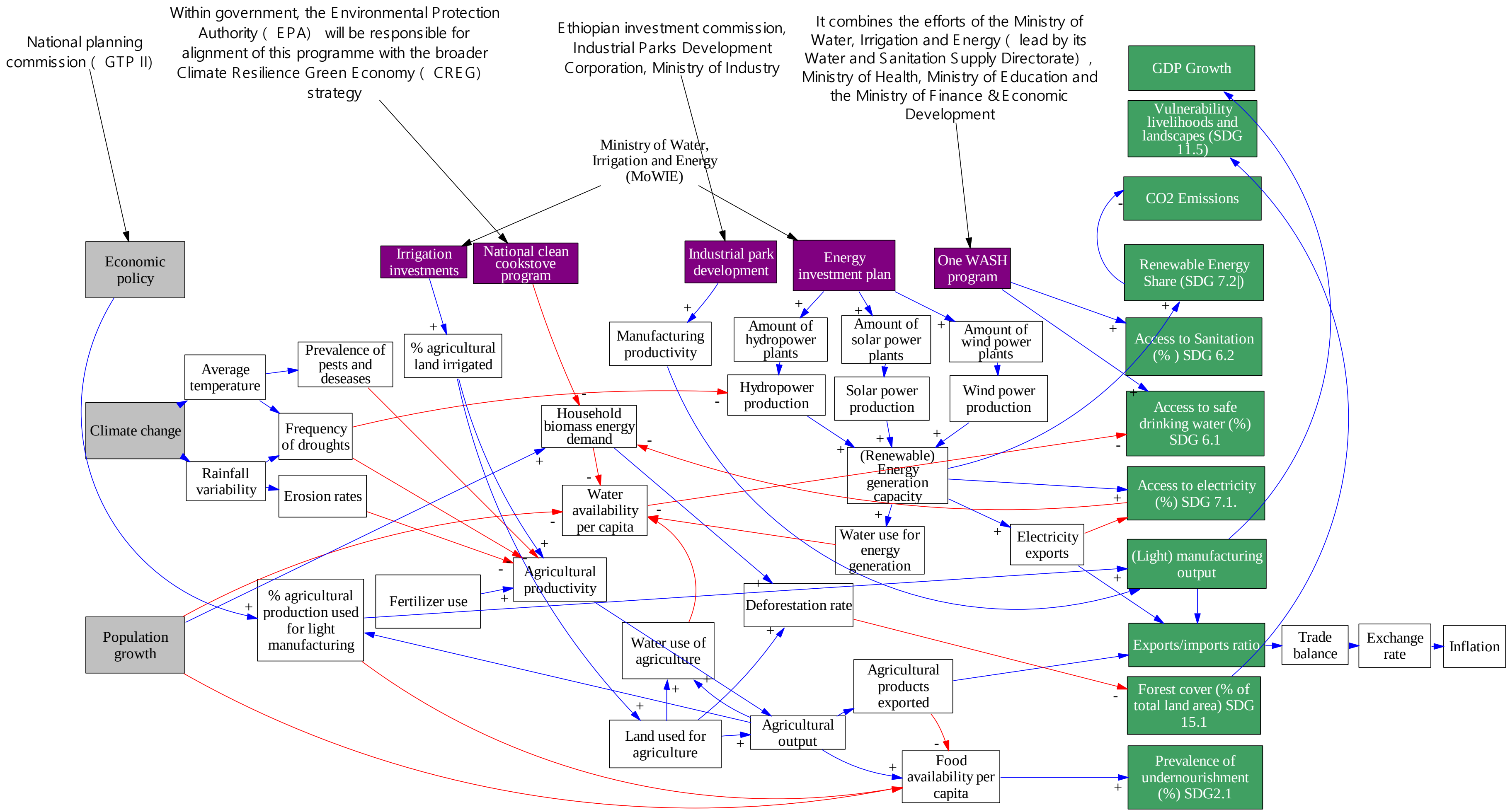
As can be seen in Figure 7 above, the future of Ethiopia's economic, social and ecological development will be dependent on the long-term sustainability of the performance of the WEF-system. The main policy objectives are visualised in the causal loop diagram representing Ethiopia's WEF-nexus in Figure 8 below. The green variables on the right hand side represent main outcomes of interest, based on the information above.

As described above, the agricultural sector will be at the core of Ethiopia's development. Agricultural output can be distinguished according to two categories; food and non-food. Both categories serve different trends that have induced the future crucial role of agriculture in Ethiopia's development. Food encompasses those agricultural products not meant for the manufacturing industry or export, e.g. staple crops and livestock. Non-food output implies products such as cotton, sesame meant for sesame paste and sugar canes.

Food production will be necessary to solve the current and future undernourishment prevalent in Ethiopia, with 32% of the population currently being undernourished. Ethiopia's population is expected grow from 104 to 140 people in 2030, making the challenge larger. This trend will pressure food availability per capita, as shown by the negative relation between population growth and food availability per capita, as illustrated in Figure 8 .

Extensive agricultural modernization combined with food imports will probably be necessary for progress in lowering undernourishment rates while keeping up with population growth. In Figure 8 this is shown by the positive correlation between agricultural productivity, percentage of land used for food agriculture and food availability per capita.

Figure 8 Most relevant Causal Loop Diagrams for the Water-Energy-Food Nexus in Ethiopia



Non-food production is crucial for Ethiopia's ambition to become a leader in light-manufacturing and sustain the planned growth rates of GDP. Industrial parks are being constructed in order to process the agricultural output and transform it into manufactured goods such as textile and garment. Besides that, exporting these goods abroad will improve the position of Ethiopia's currency, improving its capability to repay foreign debt and thereby stabilize Ethiopia's macro-economic position. This relationship is defined as positive correlation between non-food agricultural output, agricultural products exported and the exports/imports ratio.

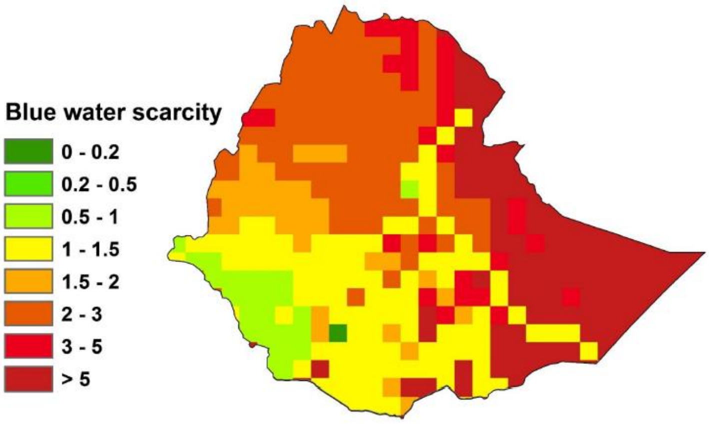
Future conflict can arise when resources (money, water) are invested in the light-manufacturing industry at the detriment of pro-poor development. Figure 8 illustrates this trade-off by assuming land used for food agriculture cannot be used for non-food agriculture and vice-versa, with a limited amount of land suitable for cultivation.

Besides the aforementioned intrasectoral trade-offs within the agricultural sector, increased agricultural output will further increase the dominant claim of agriculture on water resources. Water consumed through agriculture cannot be used for generating electricity and WASH services. The negative relation between water used for agriculture and water availability per capita and water available for hydropower in Figure 8 reflects this trade-off.

The severity of the issue of multiple sectors increasing their claim on water resources depends on Ethiopia's current and future water availability. Data from FAO's Aquastat (2018) indicates that Ethiopia currently utilizes 8.6% of its total renewable water resources. Based on this figure, one could assume sufficient water resources remain to meet Ethiopia's future water demand. However, Figure 9 below, illustrating average annual blue water scarcity, shows a different reality.

Blue water scarcity is based on the blue water footprint compared to the blue water available after environmental flows are met. Blue water entails surface water flows and connected surficial aquifers, and does not take into account deep groundwater aquifers, storage capacity and releases from dams. A value smaller than 1 implies environmental flows are met. A value higher than 1 indicates moderate (yellow), significant (orange) and severe (red) blue water scarcity.

Figure 9 Annual blue water scarcity in Ethiopia (Mekonnen & Hoekstra, 2016)



The discrepancy between Figure 9 and the perceived abundance of water resources illustrated by Aquastat (2018) exemplifies how sufficient availability of water resources depends on the temporal and spatial distribution of water. For example, around 70 per cent of the total runoff of Ethiopia's rivers occurs during the period June-September (Aquastat, 2018). Large fluctuations in water availability have led to multiple droughts in Ethiopia, with devastating effects. For example, the 2002/03 drought caused a 4% decline in GDP, a 12% reduction in agricultural output and a 15% inflation rate. In particular, coffee harvests suffered a 30% decline due to this drought (FDRE, 2014).

The influence of various actors and their policy instruments is depicted at the top of Figure 8 . It shows that economic policy set by the NPC affects the ratio between land and water used for food and non-food agriculture, assuming a limited amount of land fit for agricultural development (depending on soil characteristics, water availability etc.). Thereby, this policy steers the beneficiaries of WEF resources.

Other actors are linked to actions and plans that can alter the practical WEF system capacity and are placed on top of the diagram in the 'instruments' category. Potential WEF system capacity is unchanged as it is bound to initial endowments.

In conclusion, it can be stated that *Ethiopia's main problem is that due to its dependence on hydropower development and light-manufacturing of agricultural products, future economic growth and social development will be vulnerable to temporal and spatial water scarcity. Besides that, this increasing claim on water resources can conflict with increasing water demand for subsistence, e.g. WASH services and small-scale farming, fuelled by population growth. Moreover, Ethiopia's ecosystems are under pressure due to deforestation stemming from biofuel use and land use change. Further deterioration of ecosystem services will negatively affect water availability and quality, among other things.*

Accordingly important trade-offs and policy questions that are key to explore are:
- In what sense do the manufacturing output goals conflict with objectives for undernourishment and WASH?
- How viable is hydropower in a country with water scarcity and growing water demands? This will be explored with our models.
- Can hydropower synergize between issues? Generating electricity, providing water for irrigation, WASH?

4.2 Step 2: Forecasting and Management of Climate Uncertainty

In order to keep the analysis easier to grasp, in the application of this framework to Ethiopia we have opted for a focus on this step on the uncertainties introduced by climate change, while taking into consideration the changes in socio-economic variables introduced by the policy agenda of a country in the analysis of current and future intersectoral claims (step 1). A more complete analysis should also consider other socio-economic scenarios other than the ones considered in official documents.

4.2.1 Trends in Ethiopia's climate

Temperatures have increased over the last five decades in Ethiopia. Compared to 1960, current mean annual temperature is 1.3 °C higher. Furthermore, the average amount of 'hot days', a day with a temperature exceeded on 10% of days, has increased by 73 relative to the 1960 distribution. The average number of 'hot nights' increased by 137. Most changes occurred in the months June, July and August for both days and nights (McSweeney et al., 2010).

Precipitation trends are hard to detect due to inter-annual and inter-decadal variability in Ethiopia's rainfall. Between 1960 and 2006 no significant trend has been observed in mean rainfall in Ethiopia.

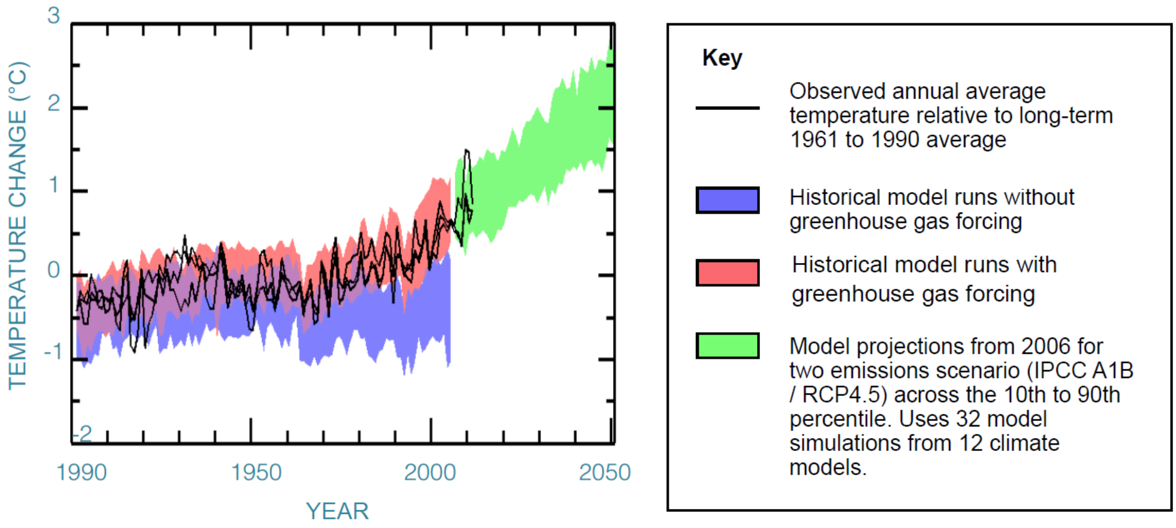
Since the 1980s, Ethiopia has experienced seven major droughts, five of them leading to localized famines. Besides that, 50% of Ethiopian households were confronted with at least one drought event between 1999 and 2004. Due to increases in temperature and erratic rainfall behaviour Ethiopia's vulnerability to droughts is expected to increase (Robinson, Strzepek & Cervigni, 2013). Droughts have a large impact on the economy, costs vary between 1% to 4% of total GDP, dependent on the intensity and duration of a drought event.

4.2.2 Future climate change

Future temperatures are expected to rise in Ethiopia, the estimated range of warming relative to the 1961-1990 period is 0.5°C to 1.5°C in the 2011-2040 period and 1.5°C to 3°C in the 2041-2070 period. Figure 10 below shows the main temperature modelling result (FDRE, 2014).

Across Ethiopia, annual rainfall variability is a common factor. The precipitation difference between a 'wet' and 'dry' year varies from 28% to 62%. This 'regular' year-to-year rainfall variability complicates the prediction regarding precipitation trends due to climate change, in terms of aggregate volume. Recent estimates taking into account different scenarios and model projections report a change in annual rainfall that varies between -25% and +30% by 2050, relative to the 1961-1990 period. Nonetheless, rainfall variability itself is expected to increase due to climate change, intensifying extreme events and making rainfall prediction more uncertain.

Figure 10 Temperature estimates for Ethiopia (FDRE, 2014)



4.2.3 Implications for policy objectives

Table 6 below illustrates Ethiopia's main policy targets that have been identified as being most vulnerable to future climate change. Each target is accompanied by its respective current and target value and time horizon. Figures have been taken from Ethiopia's GTP II (FDRE, 2016). Furthermore, the main determinants of future climate change vulnerability are elaborated per policy target. See Appendix C for additional information on the relation between climate change and trade-offs in the WEF nexus. Table 6 describes and summarises the main policy targets, see Appendix G for a more extensive overview of identified development priorities in Ethiopia, how they are connected to SDG's and the implications of climate change for their achievement.

Table 6 Ethiopian policy targets and their climate change vulnerability

Policy Target	Unit	Target Value	Current value	Time horizon	Climate change vulnerability
Major Crops Production	Mln quintal	406	270.3	2019/20	The Climate Resilience Strategy for Agriculture and Forestry (2014) indicates that the impact of climate change on agriculture could range from a modest increase in GDP of 1% by 2050 to a significant fall in GDP of 10% or more by 2050. The effect largely depends on the effect of increased temperature on rainfall, which is hard to estimate. A warmer and wetter climate could be beneficial for agricultural output, warmer and drier conditions would harm agricultural output. Higher annual and/or seasonal temperatures have been found to be directly negatively correlated with annual crop revenues per hectare. For Africa, a 1% increase in temperature would mean a 1.3% or 1.6% decline in farm revenues in regular and hotter/drier regions respectively. A future hot, dry scenario would lead to a 9% reduction in crop yields for irrigated agriculture (FDRE, 2014). The Ethiopian Water and Energy Strategy (2015) indicates that less than 10% of planned irrigation projects have undergone feasibility studies. Of the projects that are further developed, several seem to require more water than is available. It has been estimated that insufficient water supply will put $1.4 billion of targeted growth at risk. In order to improve local livelihood sustainability, "irrigation projects are planned to provide a minimum volume reserved for local community use" (p.30). Altered climate conditions will also have indirect effects on agricultural productivity. For example, the prevalence of pests and diseases will increase as temperature and humidity change. Under current conditions, pests are estimated to reduce livestock income by 40%. Besides that, climate change influences soil erosion rates, through strong winds and extreme precipitation events. Currently, agricultural GDP is negatively affected by 2% to 3% due to soil erosion. Climate change would add an additional negative effect of 1% (FDRE, 2014). Additionally, more erratic rainfall increases the frequency of floods and erosion rates. Soil erosion negatively affects agricultural productivity due to the removal of topsoil.

Policy Target	Unit	Target Value	Current value	Time horizon	Climate change vulnerability
					Gebreegziabher et al. (2011) studied the effect of climate change on Ethiopian agriculture, growth and poverty, based the effect on land productivity in moisture-sufficient highlands areas with cereal-based agriculture and the drought-prone highlands. These two areas were selected based on their large share of Ethiopia's total agricultural output. Results show that in the moisture-sufficient highlands areas crop and livestock productivity increases until 2030 in the climate change scenarios compared to the no-climate-change scenarios. After 2030 land productivity starts to decline. In the drought-prone highlands, land productivity and crop yield starts to decrease relatively soon. Additionally, the study analysed the role of general Total Factor Productivity (TFP) growth, which has been 2.58% since 1992 in Ethiopia, in agricultural productivity. Results show that climate change affects income by 30% under both scenarios (including and excluding TFP growth). However, in the scenario including TFP growth and climate change overall income level increases. Therefore, the positive effect of TFP growth outweighs the negative effect of climate change on productivity.
Area of Land developed with modern small scale irrigation schemes	Mln hectare	4.1	2.3	2019/20	Ethiopia's policy documents acknowledge the vulnerability of the planned growth in agriculture to rainfall variability. Irrigation can aid in reducing this vulnerability by distributing water more uniformly and efficiently. However, additional future reliance on irrigation systems also creates exposure to climate change. Up to $16.8m of agricultural growth has been found to be at risk under the driest scenarios due to insufficient irrigation. A further $1.4bn of targeted growth has not yet undergone feasibility study, but appears to be in areas where there is insufficient water supply (FDRE, 2015).
Power generating capacity	MW	17,347	4,180	2019/20	Mukheibir (2007) found four main consequences of altered rainfall and temperature conditions that affect hydropower output. Firstly, higher temperatures increase surface water evaporation. Secondly, dry conditions reduce surface water run-off and diminish the storage in reservoirs, reducing hydropower production. For example, historical droughts have sharply diminished African hydropower output. In 2004 all of Tanzania's hydropower plants were temporarily operating at half capacity due to a drought. A higher frequency of droughts

Policy Target	Unit	Target Value	Current value	Time horizon	Climate change vulnerability
					and/or increasing water withdrawals from other sectors is therefore expected to negatively affect hydropower output. Thirdly, flooding can increase surface water run-off and thereby increase generation potential. However, floods can carry large loads of sediments and other materials such as vegetation that can damage or block the hydropower plant. Fourthly, desertification of soils can increase erosion rates, with sediments filling up reservoirs and lessening the lifespan of hydropower plants (Mukhebir, 2007). Simplifying results gives a one-to-one relationship between a percentage change in precipitation and power generation according to Neumann and Prince (2009). However, deriving relationships from average rainfall conditions can be misleading. Average rainfall and extreme events can increase simultaneously, intensifying droughts in terms of occurrence and intensity, leading to potential blackouts (Cole, Elliot & Strobl, 2014).
Forest Coverage	%	20	15.5	2020	Current weather variability has existing impacts on forest health, for example 200,000 ha is affected by forest fire prevalence annually. Future climate change is expected to affect forest productivity and health, through changes in temperature and rainfall, affecting the suitability of existent forest areas. These effects can be exacerbated by the slow rate of natural forest adaptation and the limits on natural redistribution due to land constraints. However, adverse effects can be partially off-set by increased productivity stemming from a CO2 fertilisation effect (FDRE, 2014). Hotter, drier scenarios will result in projected reductions in the areas of forest coverage, fragmentation of forest life zones, the disappearance of certain types of forest (e.g. montane and lower montane wet forest and subtropical desert scrub). This has the potential to affect timber and non---timber forest products, wider ecosystem services (water and soil catchment management and flood protection) and rural livelihoods, which depend on forests for a large proportion of their income, and as a coping strategy during times of drought (FDRE, 2014).

Policy Target	Unit	Target Value	Current value	Time horizon	Climate change vulnerability
Overall potable water supply coverage	%	83	58	2020	A large proportion of planned schemes in the One Wash National Program rely on dug wells and spring capture. These technologies are often highly exposed to rainfall variability and options for alternative methods are limited. By 2030, around 14 million have been found to be at risk of (drink)water scarcity due to low-resilience technologies and/or climate-prone hydrogeology. Moreover, higher temperatures increase domestic water needs, further pressuring water resources available for WASH purposes. Additionally, climate change can affect groundwater resources, which are often used for domestic ends. Long-term reductions in rainfall can reduce groundwater levels. Contrarily, an increase in the intensity of rainfall has been linked to increased groundwater recharge (FDRE, 2015).

On an aggregate level, agricultural policy objectives seem to be negatively affected by climate change due to the negative correlation between temperature and crop revenues per hectare. However, the temporal and geographical distribution of climate effects varies due to Ethiopia's multitude of climatic zones. Moreover, high uncertainty remains regarding expected future precipitation, which ranges from an increase to a decrease.

The relation between irrigation policy and climate vulnerability is two-sided. Firstly, irrigation systems can mitigate drought-risk by smoothening fluctuations in water availability. Secondly, additional development of agricultural areas dependent on irrigation systems can generate additional vulnerability to climate change.

Ethiopia's aspired future hydropower output will face various threats stemming from an increase in temperature. The aforementioned uncertainty regarding future rainfall patterns complicates assessing the implications of higher temperatures for surface water run-off. Furthermore, as illustrated by section 4.5, precipitation model outcomes include high regional variability. Therefore, each planned hydropower asset can experience different climate change effects. Based on the current untapped hydropower capacity embodied in Ethiopia's water resources initial investments seem to create more added value than vulnerability.

Rural livelihoods can become particularly affected by climate change due deteriorated forest health, which serves as input to biomass energy use, and reliance on low-resilience WASH technologies. The WASH sector is especially vulnerable to an increase in rainfall variability, due to the necessary continuity of drinking water supply for subsistence. An increase in variability is expected to occur due to increased kurtosis in the probability distribution of future rainfall.

Besides climate change affecting policy objectives through altered water availability, growing economies such as Ethiopia imply an increase in conflicting water demands due to increasing domestic and industrial water needs. In terms of relative importance, Vörösmarty et al. (2000) found that "impending global-scale changes in population and economic development over the next 25 years will dictate the future relation between water supply and demand to a much greater degree than will changes in mean climate" (p. 287 Alcamo, Flörke & Märker (2007) also find that the balance in water supply and demand will be mostly affected by an increase in withdrawals, rather than decreased supply due to climate change.

4.3 Step 3: Analysis of trade-offs and synergies

By undertaking a in depth analysis of the WEF system, key interdependencies between the water-food – energy sectors we enable the explicit formulation of key policy dilemmas, which helps to elucidate the specific conflicting points and trade-offs faced by a country in their endeavour to achieve food, water and energy security along with the desired economic growth that is key for the achievement of other SDG's .

We will do this in depth analysis and illustration of the methodology for two of the three most important intersectoral claims identified throughout steps 1 and 2:

1) Water required for agricultural production: water-food nexus
2) Water required for energy production: water-energy nexus

4.3.1 Water for Food: the complex linkages between food and water security

Food production and more specifically water for irrigation accounts for over 85% of water withdrawals in Ethiopia, making the agricultural sector the largest user of water. It is known that 50% of water withdrawals for food production are lost, either evaporated into the atmosphere or transpired through plant leaves.

Causal Loop Diagram in Figure 11 shows the interdependencies between food and water security. In order to have a comprehensive understanding of the behavior of these two systems and the trends we observe in Ethiopia is important to identify critical variables of the system, which could be places of leverage. The following paragraphs will explain in greater detail this process.

To define what is a critical variable, the number of arrows coming in and coming out of this variable are a first good indication. The causal links depicted by the arrow that such variable has more causal relations influencing it and/or influences many other variables. The more connections it has, the more critical this variable could be. This is, however, not the only criteria; also the fact that such variable affects multiple “outcomes of interest” or the main goals of the system - which are at the right side of the diagram - makes it a suitable one to be considered a critical variable.

As an illustration of the previous two criteria, let’s look at *Total agricultural land* to understand how this dynamic works. On the one hand this variable is being influenced by *Total food demand, Average cultivated area, Rainfed agricultural land, Irrigated agricultural land* and *Average yield per crop.* On the other hand, this variables has an impact on *annual deforestation rate* and *Energy used for Harvesting*. According to the first criteria, this would be a central variable. However, we still need to evaluate whether it influences many of the outcomes of interest or not. To check this, the arrows that depart from *Total agricultural land* are followed. As it can be seen in **Error! Reference source not found.**, the goals *Water stress, Biodiversity, Food production environmental footprint, Hunger, Interruptions in supply and percent of energy used for productive use* are all affected by this variable. This variable could thus be considered a critical variable of the system.

Following the same principles, the variable *Average yield per crop field* does not seem at first so central, as it does not have many arrows going in or out of it. Nevertheless, given the number of final goals this variables influences - more than *Total agricultural land*- make it a critical one. Even more since this variable is easier to be influenced by a range of policy measures.

To complete this analysis is important to understand the main mechanisms that drive system behavior and explain the historical trends observed in key outcomes of interests. The behavior of a system is the result of its structure and is driven by what is called Feedback Loops. These loops are series of causal connections that altogether form a closed loop, which reinforces or stabilizes the behavior of a system.

We can observe such a loop in Figure 11, in the right side bold arrows are connected. The loop could be read as follows: An increase in the *Ecosystem’s Health* increases *river discharge levels*, as more water remains within the system. This, at the same time, increases *water supply* and consequently reduces *water stress*; which ultimately means that more water can go to Ecosystems and *Ecosystem’s health* improves. This behavior is called a reinforcing loop, as an increase in *Ecosystem’s Health* from a variable outside the loop, would increase the whole loop final outcome, and *Ecosystem’s health* itself again. Such a reinforcing loop may become, depending on the initial levels of “Ecosystem Health”, a vicious or virtuous cycle. Reinforcing loops cause exponential growth or decrease and if stronger than other loops they can steer the behavior and direction of the whole system.

As it can be observed in Figure 11, two important reinforcing loops with Ecosystems Health as departure point could become vicious cycles that deteriorate exponentially the water stress challenge and/or virtuous cycles that lead to an exponential increase of water supply. Ecosystem Health affects river discharge levels and water quality, both of which define water supply. Limited water supply and stress often means that environmental flows are not ensured and that Ecosystem Health is further deteriorated. As it can be seen in Figure 11, Ecosystem Health not only plays a role in water supply within normal conditions but also contributes to the resilience of landscapes and the reduction of economic and crop production losses in extreme dry/wet years. This seems all in all to be a leverage point of the system. Therefore is not surprising that reduction of deforestation rates is the focus of the work of many NGOs and governmental campaigns around the world.

To explain the possibilities of this type of analysis, an increase in *Average yield per crop field* will be analysed. If we assume that the yield per crop field is increased, following the lines going out of this variable, it can be observed that it decreases the *Total agricultural land*, as less land will be required, and it will also decrease the *annual deforestation rate*. This change will decrease as well the *Area of Natural Ecosystem Destroyed*, which will in turn increase *Ecosystems Health* and reduce W*ater Stress*. It can be concluded, with the same logic of the Causal Loop Diagram, the following:

An increase in average yield per crop would mean in terms of system goals a:

- Reduction of Water stress
- Increase on Biodiversity (or at least not decrease)
- Decrease in Food production environmental footprint
- Reduction of Hunger (defined as # months there is enough food per year)
- Reduction of interruptions in energy supply
- Reduction of Percentage of energy used for productive use

As it can be seen from the previous analysis, increasing the *Average yield per crop field* will be an effective and straightforward way to contribute to the accomplishment of all the goals defined. Following the same rationale, reducing the *Average yield per crop field* would affect negatively the goals proposed. Finally, by doing the same analysis we observe that decreasing *Total agricultural land* will have similar effects in the goals of the system.

What does this mean from an Ethiopian perspective? These two variables and loops are very relevant given Ethiopia's agricultural system and policy goals. With the expected growth of 50% in food production between 2015 and 2020 and assuming the rest of the system in the *business as usual* scenario, an increase in *Total agricultural land* of at least 50% can be expected, meaning that there would be a significant:

- Increase in Water stress
- Reduction of Biodiversity (or at least not decrease)
- Increase in Food production environmental footprint
- Increased in Hunger (defined as # months there is enough food per year)
- Increased in interruptions in energy supply
- Increase in Percentage of energy used for productive use

Now is important to go a step further in our analysis to understand the concept of trade-offs. In our analysis of Average *yield per crop field* and *Total Agricultural Land* and their effect on outcomes of interest we did not yet consider how the measures that could be implemented to improve these parameters, could have negative side effects and rise conflicts between goals. In Figure 11 it can be observed that a way to increase *Average yield per crop field* - which is 'desired' from the previous analyses -, is through increasing the *Fertilizer and pesticide application rate* and/or increasing irrigation and therefore *irrigated agricultural land.*

In the Causal Loop Diagram presented, *Fertilizer and pesticide application rate* do not only have a positive effect by increasing *Average yield per crop field,* but also a negative one by affecting the *Quality of irrigation return flows,* and in this way Water quality, which will eventually lead to an increase in *Water stress* and decrease of *Biodiversity.* Also, by following the causal chain or path through E*cosystems' Health,* a third goal is negatively impacted in the longer term: *Hunger*.

Here a dilemma or trade-off can be pointed out. By increasing the use of fertilizers and pesticides, two possible things can happen. On the one hand (the *Average yield per crop field* direction) all goals are improved, and thus, seems to be a fairly effective solution. On the other hand, when observing the negative side effects of fertilizer use, it is not clear what the best direction to take is. A similar dilemma can be identified when increasing *Irrigated agricultural land*. By doing this, not only the *Total agricultural land* can be reduced due to an increase in *Average yield per crop field*, but also *Water used for irrigation* and to a less degree *energy used for harvesting* will increase, eventually leading to water and energy stress and an increase on *interruptions in supply*.

In explicit terms these dilemma's or tradeoffs would be:
How to increase the average yield per crop area so as to advance water and food security, while limiting or avoiding the negative side effects of current solutions as Fertilizers and Pesticides on biodiversity and water quality and of water for irrigation on water security?

Stating the dilemmas in this way helps to elucidate the specific conflicting points and trade-offs faced within the Water-Energy-Nexus. This process also helps to formulate problem definitions that are clear and helpful for the search of climate smart strategies; strategies that are effective in the long term and deal with the root causes of Ethiopia development and environmental challenges and that have the potential to solve the trade-offs or to create additional synergies within the nexus.

To conclude, there are important trade-offs and tensions between food and water security- as an increase of agricultural land may endanger water supply in the middle to long term and traditional measures to increase average yield per crop often result in lower water quality levels, also reducing supply.

Figure 11 Causal Loop Diagram depicting the interdependencies between Food and Water Security

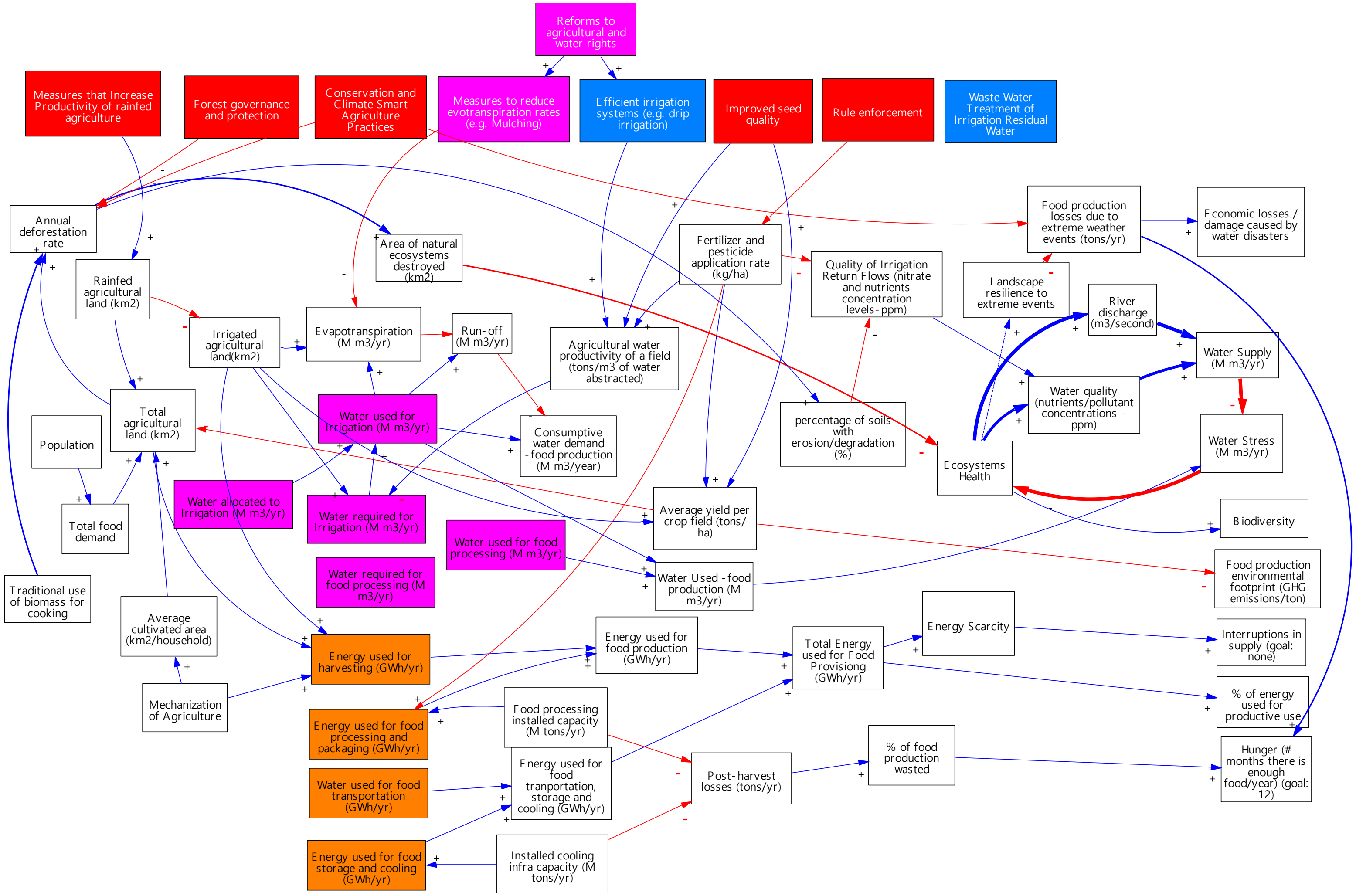
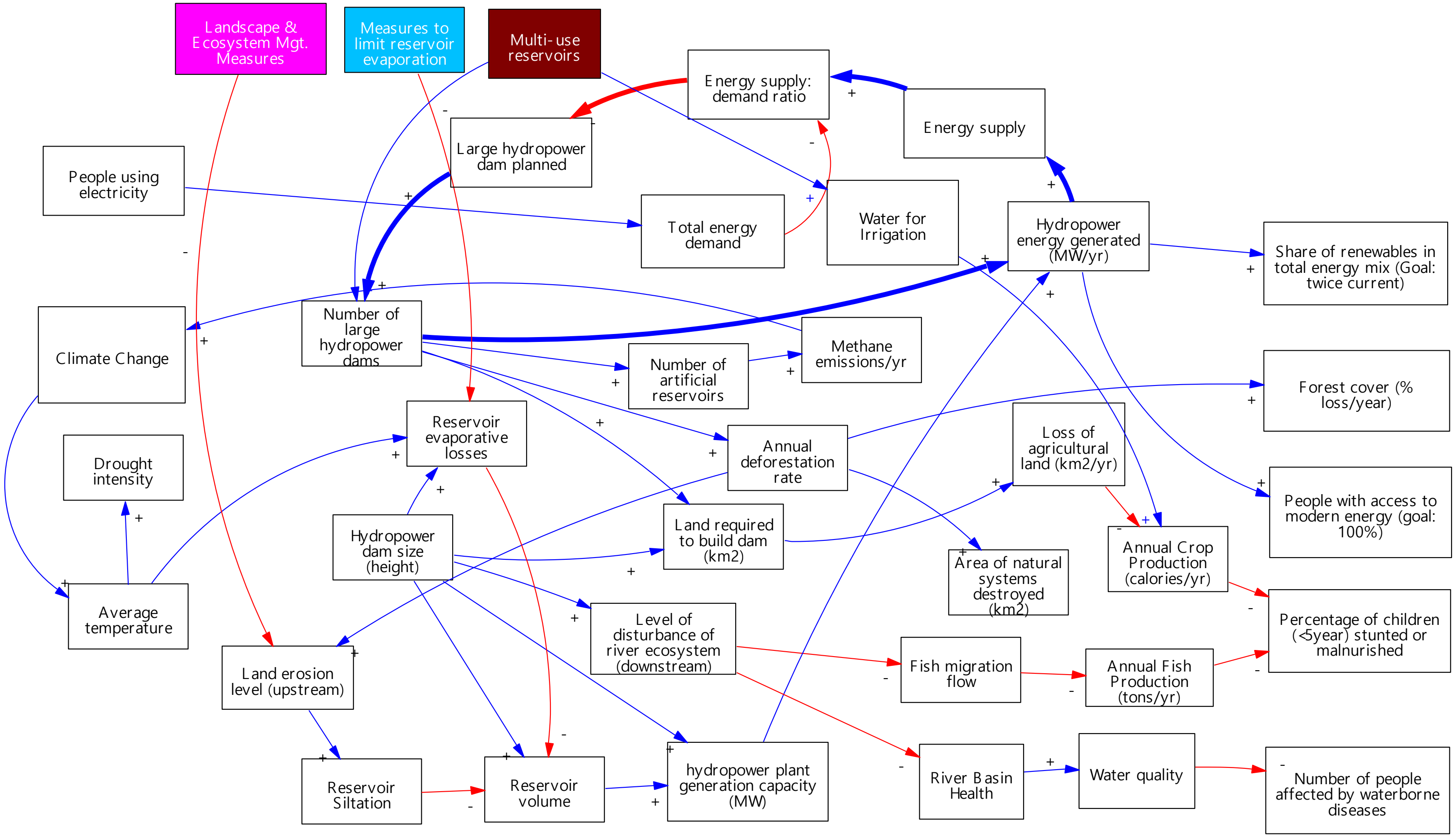


Figure 12 Causal Loop Diagram for Food and Energy Security



4.3.2 Water for Energy: the complex linkages between water, food and energy security

As an additional Causal Loop Diagram to analyse, the case of the Water for Energy trade-offs is explored. Figure 12 shows the system diagram relating hydropower development versus environmental and natural resources objectives. Following the same analysis pattern as for water for food production, the critical variables and feedback loops will be identified in this section first. Then, the implications of such variables and the dilemmas present will be explored in the Ethiopian case, and finally some leverage points will be identified that could steer the direction of the system's behavior.

As explained before, critical variables are those that either have many connections within the system or affect most or the goals. Such connections can be either going in or out of the variable. With such base, two variables and one feedback loop can be identified: *Number of large hydropower dams* and *Hydropower dam size* and the loop that is represented with bold lines in Figure 12. Now a zoom will be done in each one of them for the case in Ethiopia.

The future development of Ethiopia relies heavily on Hydropower. There is an expected increase of power generation capacity of more than 8 times between 2012 and 2030, from 1.981MW to 16.864 MW in 2030. This dramatic increase in Hydro energy production inclines the system diagram in a very straightforward way towards growth, so all that is dependent variables on *Number of large hydropower dams* will have critical effects here. Increasing the *Number of large hydropower dams* according to the logic of the system diagram, will end up increasing the *Share of renewables in total energy mix* and *People with access to modern energy* – which is desirable. On the other hand, *the forest cover* will be reduced due to deforestation, as well as the *percentage of children under 5 stunted or malnourished* due to competition of land with agriculture. All this is undesirable, of course.

There is an additional dilemma worth of highlighting from increasing the *Number of large hydropower dams*. Even though in the short term people will get access to modern energy, in the long run this goal might be threatened by climate change, from which building new dams will be also a contributor to some extent as it accelerates deforestation. Here we observe again that a policy measure will have both, positive and negative implications on the same goal in different time scales.

The loop between *Number of large hydropower dams*, *Hydropower energy generated* and *Energy supply:demand ratio* is a balancing feedback loop. This means that the tendency of the whole loop is not to increase unlimited, but to grow as the limits allow (in this case, *people using electricity*) and remain there. This is a key factor when talking about speed of implementation. We'll come back to this later.

If the actual increase of Hydro power in Ethiopia is a fact, the goals related to *People with access to modern energy* and *Share of renewables in total energy mix* will be favorably met. However, the other goals affected negatively, such as *forest cover* and *percentage of children under 5 stunted or malnourished* will have a heavy burden if they are not managed adequately, especially the negative effects on land and ecosystems when building the dams.

Doing a similar analysis for an increase in *Hydropower dam size*, at first it can be observed that it would affect positively the *people with access to modern energy,* however if analysed carefully it will also decrease it if an increase in the evaporation losses happens, reducing *reservoir volume*, and ultimately *hydropower plant generation capacity*. In this case an optimal needs to be found, and/or measures that limit reservoir evaporation. Additionally there are purely negative effects caused by the an increase on *number of large hydropower dams*, such as an increase of *percentage of children under 5 stunted or malnourished* and the *number of people affected by waterborne diseases,* both of them explained by the *level of disturbances of river ecosystems (downstream)* caused by the construction of dams, and the subsequent impacts this has on *fish migration flows* and *water quality.*

Additionally a significant increase in the *number of large hydropower dams* would not only imply and increase in *access to modern energy*, but also an increase on *number of people affected by waterborne diseases* and diseases and is expected to trigger land use conflicts (less land available for agricultural production) in the areas where the hydro dams projects will be developed. Summarizing, the dilemma faced here seem to be: *How to exploit the hydropower potential of Ethiopia without materializing the environmental, food security and health threats associated to it?* Given the ambitions plans that Ethiopia has to increase hydropower production and the significant increase in energy production planned according to the policy documents reviewed, it is very probable that most of this production will consider the construction of very large dams. Therefore it is important to consider these trade-offs when designing further a strategy of hydropower generation expansion. Based on this understanding the government of Ethiopia could design a plan that includes the necessary risk mitigation measures and climate smart strategies that allow them to increase their generation capacity while limiting the negative effects this has on the environment and ultimately on food and water security for the most vulnerable.

4.4 Step 4: formulating Climate Smart Strategies: making use of leverage points and creating synergies

Once we have formulated clear problem definitions that capture the key dilemma's and trade-offs (steps 1 to 3) these dilemma's guide our the search for Climate Smart Strategies. Climate Smart Strategies are strategies that are effective in the long term , that deal with the root causes of Ethiopia development and environmental challenges and that have the potential to solve the trade-offs or to create additional synergies within the nexus by making use of powerful leverage points.

According to Meadows (2007), there are different ways to change a system behavior and improve the performance of system, called leverage points. Some leverage points are more effective than others. What Meadows proposes is a specifically categorized way to change the behavior of a system. The following is the list of possible changes to do in order to modify the behavior of any system, in increasing order of effectiveness:

12. Constants, parameters, numbers (such as subsidies, taxes, standards).
11. The sizes of buffers and other stabilizing stocks, relative to their flows.
10. The structure of material stocks and flows (such as transport networks, population age structures).
9. The lengths of delays, relative to the rate of system change.
8. The strength of negative feedback loops, relative to the impacts they are trying to correct against.
7. The gain around driving positive feedback loops.
6. The structure of information flows (who does and does not have access to information).
5. The rules of the system (such as incentives, punishments, constraints).
4. The power to add, change, evolve, or self-organize system structure.
3. The goals of the system.
2. The mind-set or paradigm out of which the system - its goals, structure, rules, delays, parameters - arises.

1. The power to transcend paradigms.

By applying this approach to the WEF nexus, and the case of Ethiopia, different Climate Smart strategies that make use of these leverage points can be conceived.

4.4.1 Achieving food and water security

For instance, part of the solutions already proposed (Fertilizers, Irrigation and/or improved seed quality) are already part of the 12th point of the list, where some parameters are increased or decreased to change the final effects on the goals. There are still many others (maybe more effective) ways to change the behavior of the system, and we will explore some options here.

A first option that can be considered as a solution could be, for instance, the implementation of fertilizers with less harming effects in the water or the environment. This would delay the effect of chemicals on the ecosystems' health and would balance - for better - the trade-offs of that particular solution. Similar solutions could be thought for irrigation, where less energy intensive solutions could be taken, such as taking water from specific (easy to access) places, or making the spraying process more efficient. All this type of solutions could be grouped in option 9th of the list proposed by Meadows: changing *the lengths of delays, relative to the rate of system change*.

Also, some other more effective changes can be made which would take advantage of the loops already present in the system. Looking at how central are some variables in a feedback loop, it can critically improve (or worsen) the behavior of the system. In the Ethiopian case, some special focus could be put in the *Ecosystems' health.* This variable is central to the loop and affects three of the goals in the system. So for instance, reinforcing this loop by adding *forest governance and protection* policies, or even including economic incentives for families to work on this by introducing payments for ecosystem services or the like that could boost and protect these goals. Additionally reforms to agricultural and water rights could create the incentives for farmers to invest in more efficient irrigation systems and other measures to reduce evotranspiration. This type of changes is related to point 7th of the list proposed: change in *The gain around driving positive feedback loops*.

Finally, more drastic but also more effective changes in the system can be developed. Item 4 of the list, *The power to add, change, evolve, or self-organize system structure,* is definitely a point where things can be dramatically changed. These changes nevertheless require longer periods of time and a broader perspective ; for which political buy in is necessary. These changes could be, for instance, about modifying individual behaviors regarding social systems and productivity models that are resilient and environmentally friendly. An option here would be the introduction of *Conservation and Climate Smart agriculture practices*. Nevertheless, to make this happen, the modifications have to be done from the bottom, regarding education and empowerment so emergent changes come out of it. Transforming food consumption patterns is another example of how a system behavior can change if the system structure is changed by changes in individual behavior. Such a change would dramatically influence food demand in quantity and types of crops, and in this influence significantly the environmental pressures posed by food production on the water sector and the environment. We see such a change happening in the Western world were the preferences of consumers for biological products is driving the change in agricultural practices elsewhere.

The changes proposed here require different degree of commitment and implementation strategies. Independent of that, the leverage points approach helps in defining more effective policies and designing Climate Smart Strategies (CSS). For the design of Climate Smart Strategies a systemic analysis of the nexus is required.

4.4.2 Achieving energy security without endangering food and water security

A rather 'technical' solution that is in between modifying *Constants, parameters, numbers (as a 12th best way to change a system)* and changing *the sizes of buffers and other stabilizing stocks, relative to their flows (the 11th best way),* could be to tackle evaporation losses in the dams to be built in Ethiopia. In this way, harmful effects of large hydro dam regarding water losses due to evaporation could be mitigated.

A deeper change of this system could be done if *the lengths of delays, relative to the rate of system change* are modified (this is the 9th best way to change a system, according to meadows). This could mean, for instance, that in practical terms the construction of the dams can be done in a different speed in Ethiopia, making sure that the affected goals can be mitigated adequately over time. Making use of the balancing feedback loop would help to control this over time, by either helping the loop with – for example- implementing *Landscape and Ecosystem Management measures* that control erosion upstream and prevent a loss in *reservoir volume* of existing dams or slowing down the growth in *total energy demand*, so that the process of hydropower expansion matches better time wise with the environmental adjustments required. The implementation of this approach requires nevertheless an change in Ethiopia policy priorities, or at least in the tempo with which they implement national economic objectives.

A final lever that could help, is the one related to *change the rules of the system*, which is expected to have greater impact than the previous ones. This means that instead of letting the system work as it is now, new incentives and maybe new linkages are introduced; overall changing current system structure. This change of the system, for the Ethiopian case, would mean that -for instance- new regulations actually enforce the protection of some variables, like the requirement to build artificial 'fish passes' allow for *fish migration flows*. Also, creating strong regulatory and economic incentives for companies to protect the ecosystems surrounding the dams, would help to overcome the tradeoff between dams construction vs. environment and health, by changing the connections between them.

4.5 Modelling results and quantification of trade-offs and synergies

4.5.1 Brief description of the modelling framework for quantitative estimation of trade-offs and impact of climate change (steps 2 and 3)

TIAM-ECN is a well-established version of the global TIAM model developed in the context of the IEA Implementation Agreement called IEA-ETSAP (The International Energy Agency's Energy Technology Systems Analysis Program). TIAM is a member of the family of technology-rich bottom-up energy systems models based on the TIMES platform and is described in detail in Loulou and Labriet (2008) and Loulou (2008). TIAM is a linear optimization model simulating the development of the global energy economy from resource extraction to final energy use over a period of over 100 years. Its regional disaggregation separates the world in a number of distinct geographical areas, 20 until recently for TIAM-ECN. The objective function of TIAM-ECN consists of the total discounted aggregated energy system costs calculated over the full time horizon and summed across all regions. Running scenarios with TIAM-ECN involves minimizing this objective function.

The main cost components included in the objective function are investment costs, fuel costs and fixed plus variable operation and maintenance costs. Smaller cost components such as decommissioning and infrastructure costs are also included, albeit in an approximate respectively stylistic way. Since TIAM-ECN is based on a partial equilibrium approach with demands for energy services responding to changes in their respective prices through end-use price elasticities, savings of energy demand and corresponding cost variations are accounted for in the objective function as well. The database associated with TIAM-ECN includes hundreds of technologies for a broad set of different sectors: for a general description of the reference energy system of TIAM-ECN see also Syri et al. (2008).

Over the past years TIAM-ECN has been used successfully for analysis in several different domains, including on topics like developments in the transport sector (see van der Zwaan et al., 2013a; Rösler et al., 2014), the power sector (Keppo and van der Zwaan, 2012), and burden-sharing among countries for global climate change control (Kober et al., 2014). Other examples of studies with TIAM-ECN – that also provide additional descriptions of parts of the TIAM-ECN model – include work on global and regional technology diffusion (with hydropower as one of the investigated GHG emissions mitigation options: van der Zwaan et al., 2013b; van der Zwaan et al., 2016b).

We have recently replaced the previous 20-region disaggregation of TIAM-ECN by a 36-region specification, by sub-dividing Africa into 17 different geographical entities (countries or sub-regions; see van der Laan, 2015). Replacing the original representation of Africa as one single region by one in which the African continent is broken down in 17 distinct entities allows us not only to more accurately simulate developments that relate to the region as a whole (and its interactions with the rest of the world), but also to inspect in greater detail the energy systems of individual countries and sub-regions in Africa.

We hereby can connect closer to the economic and political realities of different geographical areas in Africa, which vary broadly from one country to the other. We are thus also able to better represent and analyse their specific technical and resource potentials, which diverge substantially across distinct sub-regions of the African continent, in terms of the availability of both traditional fossil fuels and renewable energy options. This article is dedicated to Ethiopia, and for its purposes we have ensured that Ethiopia's current and likely near-term energy system is represented in its entirety, including all main energy-consuming sectors and energy-providing technologies, as realistically as possible. This allows for using TIAM-ECN for long-term projections until 2050

hydrological conditions (for detailed descriptions of the model, see e.g. van der Krogt, 2016; Deltares, 2016). RIBASIM is a comprehensive and flexible tool that links hydrological water inputs at various locations in a specified region with water-users in the basin. It allows for evaluating various types of measures related to infrastructure and operational plus demand-side management, and enables inspecting a series of variables such as water quantity, water quality and flow composition. The model can also generate water flow patterns that may yield a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. The RIBASIM software package includes a range of DELFT Decision Support Systems Tools, and is designed for addressing a series of question types that relate to the water sector and water users in particular.

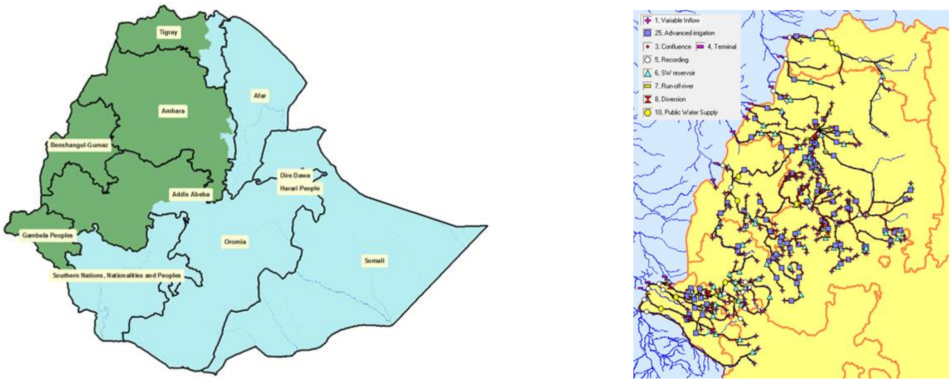
Questions that can be evaluated with RIBASIM relate to the prospects of water usage options and the potential for water resource development (for example: given available water resources and their natural variations, to what extent can a river basin be developed in terms of reservoirs, irrigation schemes and supply systems, while avoiding crop damage or harm to other water users; when and where can conflicts between water users occur, such as between hydro-power production and agricultural development, or industrial development and the degree of water pollution in a basin; what is the potential for hydropower production in a basin?).

Likewise, infrastructure requirements and operational plus demand-side management issues can be assessed (for instance: what is the effect of technical measures to improve water supply for various users, taking into account water quantity and flow composition; what are the agricultural production yields and costs for the implementation of such measures?). More generically, RIBASIM allows for performing essentially any type of analysis that requires the water balance of a river basin to be calculated, by taking into account the use by and drainage from agriculture, the use by and discharges from industry, domestic water demand for drinking, cleaning and sanitation purposes, and downstream re-use of water. The resulting water balance can provide the basic information needed to determine the available quantity and quality of water, as well as the composition of the water flow, at any time and location in the river basin.

RIBASIM has recently been used to perform an analysis for Ethiopia. It has now been updated for the purpose of this study to reflect as accurately as possible the present water basin features in Ethiopia. The analysis behind the current study makes use of the existing RIBASIM schematization developed under the ENWSM (Development of the Eastern Nile Water Simulation Model) project, commissioned by ENTRO (Eastern Nile Technical Regional Office) to Deltares. The present study makes use of the ENTRO version of the RIBASIM model only for the Blue Nile in Ethiopia, with substantial improvement with regards to the details of domestic and irrigated water demand projections, and the sequential inclusion of hydropower development in our time horizon until 2050. Model improvements also include climate change projections based on the regional climate scenario HadGem2 RCP2.6 (see Collins et al., 2008; Jones et al., 2011), downscaled at the sub-regional level to generate both climate and hydrological input for the model (for a detailed description, see Boccalon, 2016).

RIBASIM is here only used for the upstream portion belonging to Ethiopia (and therefore disregards any influence that projected future water use scenarios in the Ethiopian section of the Blue Nile might have on downstream users in South Sudan, Sudan and Egypt). Although by just simulating the Blue Nile part of Ethiopia the current version of RIBASIM only covers about 32% of the entire surface of the country (see Figure 10), we calculate that still about 70% of the total surface water availability is covered, so that the model fits our purposes (for the specifics of this claim, see Boccalon, 2016).

Figure 13 Blue Nile area in Ethiopia (left, in green) and RIBASIM model schematization of surface water reservoirs and irrigation nodes in the Blue Nile river system (right).



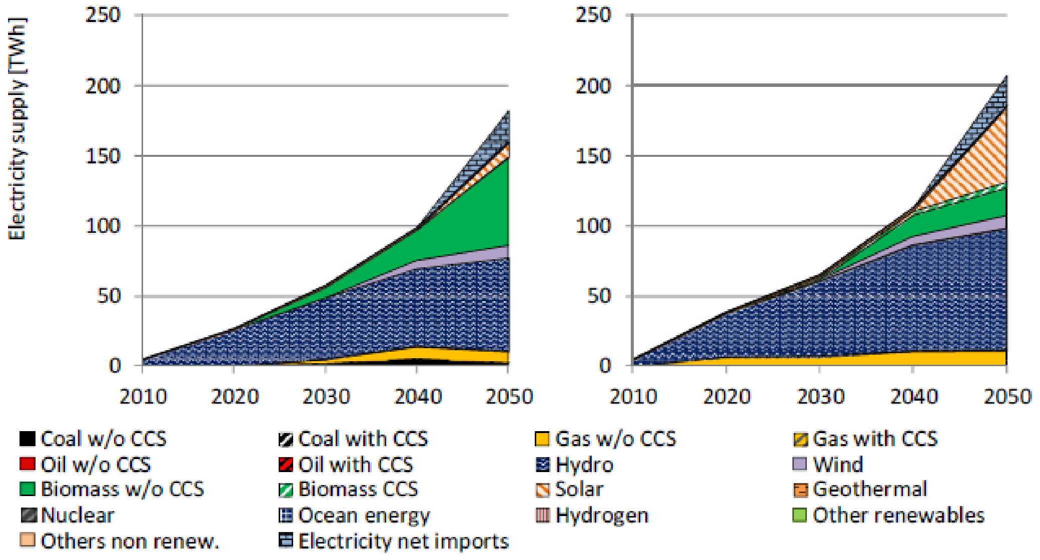
Based on an inventory of all existing and foreseen hydropower projects in Ethiopia, we estimate that about 63% of the total planned domestic hydropower capacity will have been developed in the Blue Nile river system by the time horizon of 2050. We stipulate, correspondingly, that approximately 63% of the overall national hydro-electricity generation will emanate from the Blue

Nile basin by then. By way of comparison, on the basis of existing public information, the estimated current installed capacity at the Blue Nile basin scale only covers 24% of the total national figure. In 2015 around 890 MW of reservoir-based hydropower capacity and 540 MW of run-of-river-based capacity was installed in the Blue Nile river basin of Ethiopia. In scenario R1 we assume that these numbers remain unaltered. We project that these figures are raised to 14400 MW and 750 MW in 2030 (scenario R2), and 16360 MW and 960 MW in 2050 (scenario R3), respectively.

4.5.2 Water-energy trade-offs

TIAM-ECN was employed in combination with RIBASIM to test the implications of energy developments for water availability in Ethiopia. Two energy production scenarios were computed; a baseline and stringent climate change control scenario. The former is a representation of what Ethiopia's energy system may look like without the introduction of far reaching climate policy. The latter, entitled RCP2.6 (Based on a Representative Concentration Pathway with an anthropogenic radiative forcing of 2.6 W/m2). is a scenario in which the likelihood is high (around 70%) that the global average atmospheric temperature increase stays below 2 degrees Celsius, including the relevant (global) policy measures that achieve this future. TIAM-ECN provides a projection on the optimal distribution of energy supply by technology and resource for each scenario, as depicted in Figure 14 below.

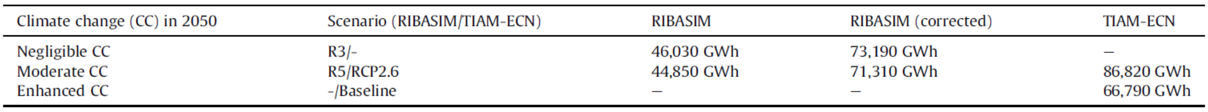
Figure 14 Electricity supply in Ethiopia by technology and resource in two scenarios: baseline (left) and RCP2.6 (right).



RIBASIM was used to calculate the produced amount of hydropower based on projected expansions plans of hydropower in Ethiopia. Two future climate scenarios were taken into account for these calculations, a baseline and HadGem2 RCP2.6 climate scenario respectively. The potential hydropower output results were compared to the hydropower outcomes depicted in figure 1 in order to assess the feasibility of scenario-based energy supply expansion from a water availability perspective.

Column 3 of Table 7below lists the annual average hydro-electricity generation levels (in GWh) in 2050 for the first two climate futures calculated with RIBASIM. Since the RIBASIM model developed for this case study only covers the Blue Nile basin and thereby only 63% of the expected hydropower capacity in 2050, we list in column 4 these numbers corrected (i.e. multiplied by a factor 100/63) so as to reflect the full amount of hydropower likely to be produced on a national scale by then. The last column indicates the values that TIAM-ECN projects for hydro-electric energy production by the middle of the century, for the last two climate futures.

Table 7 Main results from the RIBASIM and TIAM-ECN models for annual average hydropower generation in 2050



Climate change (CC) in 2050	Scenario (RIBASIM/TIAM-ECN)	RIBASIM	RIBASIM (corrected)	TIAM-ECN
Negligible CC	R3/-	46,030 GWh	73,190 GWh	–
Moderate CC	R5/RCP2.6	44,850 GWh	71,310 GWh	86,820 GWh
Enhanced CC	-/Baseline	–	–	66,790 GWh

The first observation from Table 7 is that in the moderate climate change scenario (R5 and RCP2.6, respectively, for RIBASIM and TIAM-ECN) the projected level of hydro-electricity generation in 2050 in RIBASIM (71,310 GWh) is substantially lower than that in TIAM-ECN (86,820 GWh). This means in principle that the cost-optimal amount of hydropower production is higher than the amount that we think is technically feasible from a hydrological, water balance and climate change point of view. The discrepancy in findings with our two models can be explained, however, by the fact that RIBASIM does not include any plants that are not yet in some stage of planning, while opportunities exist for the inclusion of more small-scale hydropower projects.

In other words, in order to achieve the large amount of hydro-electricity production that TIAM-ECN foresees, a capacity would need to be installed by 2050 that even goes beyond what is foreseen in current plans and intentions (for a total of 28 surface water reservoirs and 5 run-of-river plants). The explanation for the large amount of hydropower production projected by TIAM-ECN is that it is the level deemed required from the model's cost-minimisation perspective in order for Ethiopia to contribute its share in global climate change control while meeting domestic demand for energy services.

In the negligible climate change case, we see that RIBASIM foresees an average annual hydro-electricity generation level of 73,190 GWh in 2050, which is about 3% higher than in the moderate climate change case. This is consistent with the observation that on average there is slightly more precipitation on a national scale in this negligible climate change case than in the moderate climate change case. In the enhanced climate change (that is, baseline) scenario TIAM-ECN projects an amount of produced hydropower electricity of 66,790 GWh, which is a drop of approximately 23% from the level calculated under the RCP2.6 scenario. This is a reflection of the assumption that under the business-as-usual emissions pathway, little effort is undertaken in Ethiopia, as well as on an international level, to manage global climate change.

The still sizeable level of hydro-electricity generation mostly derives from economic and development arguments, rather than targeting specifically climate change control. The hydropower generation levels depicted in Figure 14 Electricity supply in Ethiopia by technology and resource in two scenarios: baseline (left) and RCP2.6 (right). are derived from installed capacities of around 15 and 20 GW in 2050 for our two scenarios, baseline versus RCP2.6, respectively. The capacities stipulated for RIBASIM are a little over 15 GW and close to 18 GW, for the R2 and R3 scenarios, in 2030 and 2050, respectively. All these figures fall well within the overall domestic potential of 45 GW as reported by national authorities in Ethiopia such as the Ministry of Water and Energy (MWE, 2011). Our model outcomes are thus realistic from that point of view.

The hydro-electricity generation numbers we calculated also match economically and technically feasible hydropower capacity estimates from other analysts, as well as ambitious long-term national electric power development plans of EEPCO, of around 30 GW in 2050 (Block & Strzepek, 2012; Boccalon, 2016). The upper value of our estimates is about 10 GW below this figure of 30 GW, so in order to satisfy overall electricity demand perhaps Ethiopia does not need to reach the total hydropower capacity level that some of its national institutions suggest today.

Policy implications

From a purely energy-cost and water-quantity point of view, our analysis may not give substantial reason to oppose the ambitious development trajectory for hydropower in Ethiopia as currently planned by national authorities. While we did not investigate whether the government's targets for economic growth and welfare increase could perhaps be met with low-carbon options other than the large-scale use of hydropower, our partial equilibrium cost-minimisation approach shows that broad hydropower development could meet the targets without simultaneously significantly increasing GHG emissions. A large increase in hydropower derives from the scenarios considered in our study through both models that we employ. Our modelling efforts, however, are merely based on an economic and hydrological approach, and thus do not account for a series of other relevant factors, among which environmental, geopolitical and social.

Such factors may induce the Ethiopian government to take a different course and reduce its ambitions substantially. According to the comparison of model results reported in Table 7 Main results from the RIBASIM and TIAM-ECN models for annual average hydropower generation in 2050 we can see that Ethiopia may not be able to meet its domestic energy demand and climate change control contributions by only relying on the intended hydropower development plans. Based on the results of our investigation we suggest that the Ethiopian government invests more effort into identifying an energy and water sector policy framework that meets internal demand for electricity and water resources while complying with its commitments under the Paris Agreement. This framework should include a broad range of renewable energy sources, energy saving options and water use efficiencies, in order to avoid an overreliance on natural water resources.

The scenarios investigated in our study and the level of detail used in our computations suggest that possible future climatic trends will not substantially impact hydropower production on a national level, even while non-negligible hydro-electricity generation reductions of around 3% may result from climate change. Yet at the local level individual hydropower plants may be subject to precipitation variability emanating from climate change that could lead to larger hydropower production losses than on average nation-wide.

The large expansion of the use of hydropower as described in this paper necessitates significant financial and human capacity investments, as well as extensive planning, institutional plus regulatory development and capacity building. These requirements will need to be complemented by efforts to reduce vulnerability to variability at the local level as a consequence of climate-dependent water availability. Our hydro-electricity generation findings are consistent with those by Block and Strzepek (2012), who report hydropower production levels between 40 and 70 TWh in 2040e2050 under varying assumptions with regards to future climate change developments in Ethiopia. This reinforces the reliability of our analysis, as well as our finding that on economic, hydrological and climatic factors alone the Ethiopian government may not necessarily have to immediately stop investing in domestic hydropower development through dedicated national policy schemes.

4.5.3 Energy-Food/Land trade offs

In this section, a simple modelling approach is presented and used to assess the demands of land and water needed to achieve a certain amount of biomass. We will look at two cases the first will focus on the land requirements for forest biomass and the second will look at food production. The calculations are very simple and provide not more than a first impression on whether and which issues might be limiting or problematic. More in-depth calculations which could be prompted by the results are possible using soil-crop models (refs). However, when going into more detailed modelling the available data

Introduction to forest biomass calculations

In this scoping study the biomass and food production levels are calculated using rudimentary methods. It provides a fast first order of magnitude using basic information, simple conversion factors and reasoning that can be followed and implemented by non-experts. The results provide an order of magnitude and direction of change and If needed further exploration can be done using more complex models which require more detailed input and expert knowledge. For more details on crop modelling see for example van Ittersum et al. (2003).

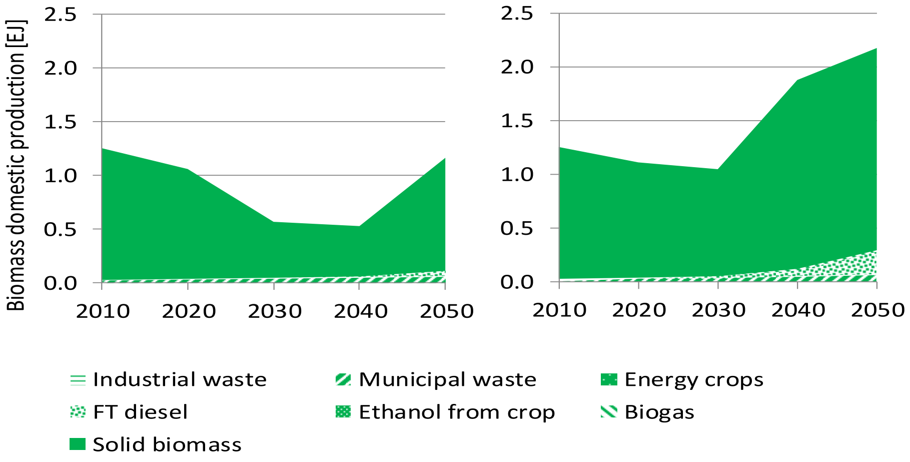
Biomass demand and implications for area and water

The first question we will address is whether the biomass needed to fulfil demand can be met by harvesting biomass from Ethiopian forests and how much water is needed. We will focus on Eucalyptus, which was introduced in Ethiopia in the late 19th century and is used mainly as fuel, although some wood is used as construction material (Pohjonen, and Pukkala, 1990).
We will use a three step approach to address the question. First we will calculate the demand second then the area needed and third the water needed to produce the amount of biomass needed is calculated.

Step 1. Calculate Demand for wood

a) This information is provided by the energy analysis, from Figure 15we see that the demand in 2010 is set at 1.1 EJ in 2010 and in the high biomass scenario about 1.9 EJ is derived from biomass. When converted to GigaJoules we get 1.1 10^9 and 1.9 10^9 GigaJoules/year for 2010 and 2050 respectively.

Figure 15 **Biomass demand**



b) To be able to determine how much biomass is needed we need to convert to kg biomass. This is done by using a conversion factor of 17 GigaJoule/ton wood (Pérez et al 2006).

Given the results in a) we get 6.47 10^7 and 1.12 10^8 ton wood/yr for 2010 and 2050 respectively.

c) The wood density for Eucalyptus of 0.58 (ton/m^3) is taken from FAO (1997). Which gives us 1.12 10^8 and 1.93 10^8 m^3 wood/yr for 2010 and 2050 respectively.

So now we have both the weight and volume of wood needed in 2010 and 2050 to fulfil current demand and the highest future demand. In forestry m^3 is used to indicated productivity. So next step is to convert the volume to the area needed.

Step 2. Area demand

a) First we need to figure out the annual production and the period or rotation the crop is grown. From Gessesse, and Teklu (2011) we get quite a large range for Eucalyptus productivity in Ethiopia: 10 – 57 m^3 wood/ha/yr. We will use both numbers for our analysis, assuming all wood is used as biofuel. Temesgen (2016) indicate that short rotations (5–10 years) for Eucalyptus plantations in Ethiopia are normal, we will assume a rotation of 7 years for our calculations. For a 7-year rotation the total volume is then 70 – 399 m^3 wood/ha which. Using the results of step 1.c and a production of 70 m^3 wood/ha we get 1.59 10^6 ha and 2.75 10^6 ha for 2010 and 2050 respectively. For a production of 399 m^3 wood/ha this is 2.80 10^5 ha and 4.83 10^5 ha for 2010 and 2050 respectively.

b) According FAOSTAT (http://faostat.fao.org) the total forest area in Ethiopia is 1.23 10^7 ha. So with 10 m^3 wood/ha/yr the required areas in 2010 is about 90% of the total forest area, whereas in 2050, assuming that the forest area doesn't change, this would require 156% of the area. So with the low productivity it would require more forest area than currently available. For a productivity of 57 m^3 wood/ha/yr the 2010 area demand is 2% and in 2050 27% of the area. In fact with a productivity of around 38 m^3 wood/ha/yr in 2050 the demand can be fulfilled on the total forest area.

Step 3. Water demand

The amount of water required to produce the required amount of biomass is calculated using a water use efficiency of 1.8 kg wood/m^3 of water for a normal year (Stape, et al., 2004). Stape et al. indicate that for a wet year this conversion is 3.2 wood/m^3. We will use the 1.8 kg wood/m^3/yr and assume the normal rainfall is valid for the 2010 and 2050 period, clearly with a dryer climate this factor would go down. We know the amount of wood needed (Step 1c) and can simply determine the amount of water needed in 2010 3.59 10^{10} m^3 and for 2050 it would be 6.21 10^{10} m^3 water. Using the forest area in Ethiopia of 1.23 10^7 ha (FAOSTAT) as reference this amount of water would be equal to a bit more than 500 mm per year over the forest area.

Climate Change

Impacts on the production levels via higher temp, water availability and change in abundance and occurrence of pest and diseases is not clear. A simple approach would be to assume reduction levels (eg: 10% 20% 50%) reduction levels in relation to possible changes. This linear relation is not worked out.

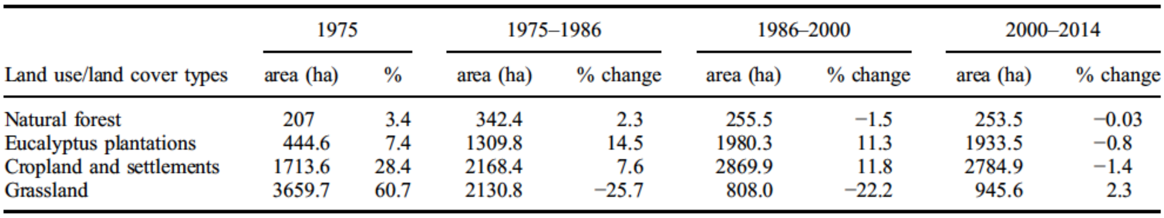
Introduction to food production calculations

The population of Ethiopia is expected to increase from 91 million in 2013 to 100 million by 2020, 120 million by 2030 and 145 million by 2050 (Ministry of Environment and Forest, 2015). Agriculture is key sector in keeping economic growth and development in pace with the increased

demand for jobs, income and food. In this section we will focus on the cereal production which for the major share of agricultural
GDP In line with this policy aim the production and productivity of major crops is priority in the draft Second Growth and Transformation Plan (National Planning Commission 2015).

Achieving an increase in production can be achieved by increasing the area and the output per unit area. From we can see that the increase in cropland area has been an important strategy for decades but since the turn of the century this strategy has become less important.

Table 8 Summaries of land use and land cover from 1975 to 1986, 1986 to 2000, and 2000 to 2014 time periods showing area changed in hectares and percentage change (Desalegn et al., 2014)



	1975		1975–1986		1986–2000		2000–2014	
Land use/land cover types	area (ha)	%	area (ha)	% change	area (ha)	% change	area (ha)	% change
Natural forest	207	3.4	342.4	2.3	255.5	−1.5	253.5	−0.03
Eucalyptus plantations	444.6	7.4	1309.8	14.5	1980.3	11.3	1933.5	−0.8
Cropland and settlements	1713.6	28.4	2168.4	7.6	2869.9	11.8	2784.9	−1.4
Grassland	3659.7	60.7	2130.8	−25.7	808.0	−22.2	945.6	2.3

In this section we will look at maize as a key cereal crop. Over the 2010-2014 period production has increased from 2.5 t/ha to 3.4 or 36% (see Table 9)

Table 9 Ethiopia production levels maize 2010 – 2014 (FAOSTAT, 2016)

Year	t/ha
2010	2.5
2011	2.9
2012	3.0
2013	3.3
2014	3.4

The production increase over the years has been a major achievement and is the result of a combination of factors including improved varieties, better fertilizer use and improved farmers' skills. Water is an important input but not likely to be the key factor for cereal production in Ethiopia. We will show this by simple calculations using basic relations and factors. The assumptions are not much different from those used in advanced models such as WOFOST and CERES but require less detailed input the results are only a first rough indication.

Water and nitrogen limited production

Assume an area with an annual rainfall of 500 mm which falls during the growing season. If only 50% of this water is used by the crop, 250 mm per year is transpired which is 2.5 10^6 litres per years. Note that both the rainfall and transpiration of 50% are at the low end. Considering a water use efficiency (WUE) of 200 litres of water needed for 1 kg dry matter we get a biomass production of 12.5 t/ha/yr. Of this total biomass about 10-20% is roots, we will use 15%. So above ground biomass is 10.625 kg per year. With a harvest index or the ration of grain to the total above ground biomass of 0.35 the harvested grain is about 3.7 t dry matter/ha/yr. If we convert to fresh yield (as reported in Table 9) assuming a moisture content of 15% in the grains we get a yield of 4.4 t/ha/yr. Which indicates that given the assumptions there is still scope to increase production levels.

The importance of soil organic matter in the soils for agriculture is many fold besides water retention, anchorage the supply of nutrients, mainly nitrogen, are important. Given a topsoil of 15 cm and bulk density of 1200 kg/m^3 we have a soil mass per ha of 1.8 t. Assuming 2% soil organic matter which is, given a 0.58 conversion factor, about 1.16 % soil organic carbon. So a total of 21 ton of soil organic carbon per ha is available over 15 cm. Converting this to total carbon can be done using 1.33 (based on Walkley and Black, 1934) gives 27 t organic carbon per ha in the topsoil. With a CN ratio of 10 this is equal to 2.7 t N/ha/yr. This N is released during the mineralisation of the SOM which is 2% per year, so given a growing season of 3 months about 14kg N becomes available to the crop. Using a conversion of 55 kg grain per kg N we get a N limited yield of 764 kg/ha/yr. This number is well below the actual yields reported in Table 9 and indicate that fertilizer is used.

The calculations show there is still scope to improve production levels. So how efficient the fertilizer is used and whether application can be improved is for further study. Also the role of irrigation in intensification of production system is worth exploring. By reducing risks related erratic rainfall and expanding the growing season irrigation can be a worthwhile investment in overall agricultural development.

4.6 Economic analysis of water-energy trade-offs

To further decide on the preferred strategies to solve these trade-offs and ensure climate resilience of investments in economic growth is required an analysis of cost-effectiveness of alternative adaptation measures. For this analysis a quantification of the trade-offs making use of models is necessary. We illustrate the use of the method we have developed to make the economic analysis of trade-offs for the case of hydropower investments in the context of the water-energy nexus.

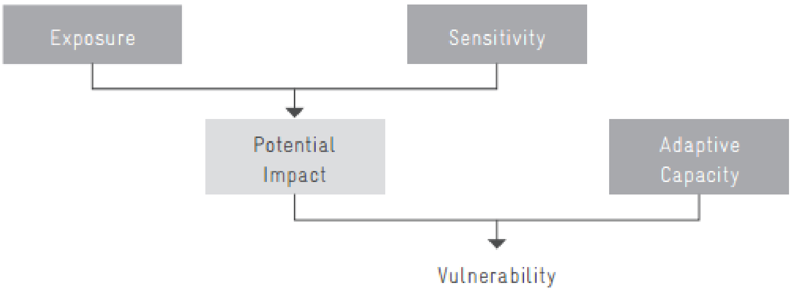
This section aims to assess the cost-effectiveness of an adaptation measure with respect to a climate change induced decrease in water availability in the hydropower sector of Ethiopia’s Blue Nile. Based on modelling outcomes of the RIBASIM schematization explained in section 4.4.1 physical effects in the Blue Nile basin of Ethiopia are transformed to costs and benefits. The valuation of water and energy shortages is performed according to their ‘total’ value, taking into account the social dimensions of water and energy supply (see Table 10).

The monetization of physical effects allows for the construction of a Net Present Value (NPV) analysis that has a uniform valuation mechanism across all sectors. By having a multi-sectoral overview of the effects one can construct a NPV analysis from the perspective of different sectors. The objective is to indicate how the NPV of an investment in adaptation to climate change varies when multiple sectors are taken into account.

An adaptation measure should decrease the increasing vulnerability due to climate change of Ethiopia’s WEF-system, and can be implemented in any sector. Vulnerability, according to the IPCC (2012) definition is “the propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events” (p.31) and “is related to predisposition, susceptibilities, fragilities, weaknesses, deficiencies, or lack of capacities that favour adverse effects on the exposed elements" (p. 32).

The vulnerability framework below (Figure 16 Vulnerability framework (AGO, 2005)) conceptualises vulnerability as a function of exposure, sensitivity and adaptive capacity. For bearing the risk of vulnerability it is necessary to be exposed to this risk. Exposure refers to having resources located in a potentially dangerous setting, i.e. an area that is sensitive to climate variability (IPCC, 2012).

Figure 16 Vulnerability framework (AGO, 2005)

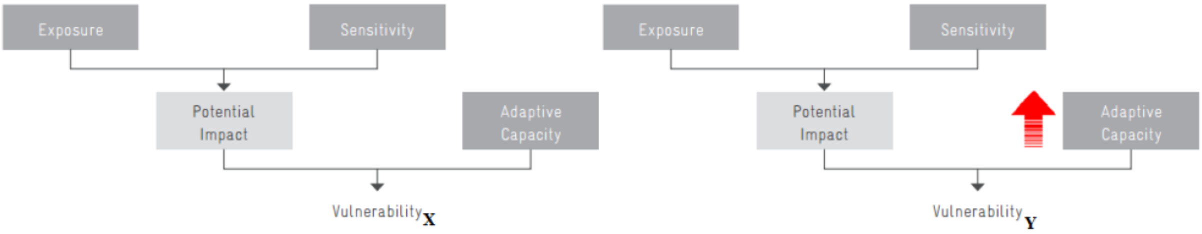


The adaptive capacity, i.e. potential adaptation measures, of a certain nation or area can be assessed according to the vulnerability framework above. Firstly, the need for adaptive investments is indicated by the potential impact climate change might have on a certain area. Based on climate scenarios, which are based on future emissions, land use and demographic trends, the exposure of a certain area/population can be computed. Relating this to the sensitivity of a sector, exposure generates a potential impact, which can be reduced by increasing adaptive capacity (AGO, 2005). Given the sensitivity of hydropower to climate change and dry conditions in general, Ethiopia's development of hydropower assets an area sensitive to droughts can be identified as an increase in exposure.

4.6.1 Economic appraisal of resilience gains

The impact of an adaptation measure is defined as the difference between vulnerability to climate change under different options, either including or excluding an adaptation measure. Figure 17 below conceptualizes the options analysed in this study; no adaptation (x) and an increase in adaptive capacity (y).

Figure 17 Adaptation options (Modified from AGO (2005))



Translating the impact of an adaptation measure to a general function framework gives:

$$Impact_y = f(Vulnerability_x) - f(Vulnerability_y)$$
(1)

With,

$$Vulnerability_x = f(Adaptive\ capacity_x, Exposure, Sensitivity)$$
(2)

$$Vulnerability_y = f(Adaptive\ capacity_y, Exposure, Sensitivity) \qquad (3)$$

With,

$$f'(Adaptive\ capacity) < 0$$
(4)

$$f'(Exposure) > 0 \qquad (5)$$

$$f'(Sensitivity) > 0 \qquad (6)$$

Besides affecting the vulnerability to climate change, adaptation measures affect other sectors. For example, in an interdependent system, such as the water-energy-food nexus, adaptation measures interfering with the water allocation can induce or mitigate shortages basin-wide. Therefore, the ultimate impact of an adaptation measure will be:

$$Impact = f(Vulnerability_x) - f\left(Vulnerability_y\right) \pm costs/benefits\ other\ sectors \qquad (7)$$

For the Ethiopia case, the cost-effectiveness of a reduction in distribution losses of urban water supply will be assessed. Hydropower output vulnerability due to climate change in 2040-2070 is modelled including ($Vulnerability_y$) and excluding ($Vulnerability_x$) the adaptation measure. The adaptation measure is expected to affect the water balance in the agricultural and/or domestic water sector, represented by the difference in average water shortage in both sectors. Altered electricity output and water shortages are valued according to their respective price, described in table X below.

Table 10 Value of water and energy in different sectors

Sector	Value in US$ (unit)	Source
Hydropower	0.09 (KWh)	EES (2016)
Irrigation	0.10 (m3)	Hellegers & Perry (2006)
Domestic	1.00 (m3)	Hellegers, Droogers & Immerzeel (2013)

The acquired RIBASIM results are implemented into a CBA and discounted towards their current value to calculate the NPV according to the format in Table 11 below.

Table 11 CBA of increasing adaptive capacity according to vulnerability framework

	Year 0	Year 1	Year 2	…	Year 30
Benefits		$f(Vulnerability_x) - f\left(Vulnerability_y\right) + benefits\ in\ other\ sectors$	$f(Vulnerability_x) - f\left(Vulnerability_y\right) + benefits\ in\ other\ sectors$	…	$f(Vulnerability_x) - f\left(Vulnerability_y\right) + benefits\ in\ other\ sectors$
Costs	C_0	*Costs in other sectors*	*Costs in other sectors*	…	*Costs in other sectors*
Total		$Impact$	$Impact$	…	Impact
NPV	…				

In order to determine if benefits outweigh costs the sum of future costs and benefits is translated into a NPV. The NPV is calculated according to the following formula:

$$NPV = -C_0 + \frac{Impact}{(1+r)^1} + \frac{Impact}{(1+r)^2} \cdots \frac{Impact}{(1+r)^{30}} \qquad (7)$$

With,

$$C_{0y} = Upfront\ investment \qquad (8)$$

$$Impact_y = f(Vulnerability_x) - f\left(Vulnerability_y\right) \pm costs/benefits\ other\ sectors \qquad (9)$$

$$r = Discount\ rate$$

(10)

The NPV will be calculated for a discount rate of 2% and 5%. With 2% indicating the long-term risk-free return on an investment such as a U.S. treasury bill[14], 5% represents a return of an Ethiopian treasury bill.

4.6.2 Results

Table 12 depicts the results, reducing distribution losses in the urban public water sector (y) decreases annual hydropower vulnerability by 54 GWh. Besides that, the average annual urban public water shortage is decreased by 12 MCM and agricultural shortages are unchanged.

Table 13 presents the transformation of physical effects to costs and benefits in US$. The reduction in vulnerability through a reduction in distribution losses produces an annual benefit of 4.78 for the hydropower sector. The public water sector annually benefits 12.7 million US$ due to decreased shortages.

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[14] https://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=longtermrate

Table 12 Average annual vulnerability and effect on other sectors of different adaptation measures

	Average hydropower output (GWh)	Average irrigation shortage (MCM)	Average public water shortage (MCM)
Historical climate	44121	501	6
RCP 2.6 climate	43013	250	31
Vulnerability (x)	1108		
Reduce distribution losses	43067	250	19
Vulnerability (y)	1054		

Table 13 Benefits/costs of different adaptation measures in millions (US$)

	Hydropower	Agriculture	Public water	Multi-sector
Reduce distribution losses	4.78	0	12.47	17.25

Table 14 depicts the NPV analysis of a reduction in distribution losses. Costs of reducing distribution losses in the urban public water sector are based on a study by Droogers, Butterfield & Dyszynski (2009), who analysed adaptation options for the hydropower sector in Kenya. Improved urban water consumption in Kenya was modelled as a reduction in supply from 14 m^3 to 10 m^3 (28%) per capita per year and increased consumption from 30% to 40%. Costs of this adaptation measure were estimated at US$ 10 per capita. The urban population in this case study is estimated at 25,336 million, therefore costs are determined at 253.37 million US$. 10 US$ per capita can be considered an upper bound estimate since the water supply in this analysis is improved by 25% instead of 28%. Changes in consumption depend on the reduction in shortages per location as computed by RIBASIM.

Table 14 NPV of reducing urban distribution losses in millions (US$)

	Year 0	Year 1	Year 2	…	Year 30
Benefits		17.25	17.25		17.25
Costs	(253.37)	0	0	…	0
NPV (2%)	133.64				
NPV (5%)	12.27				
IRR	5.42%				

The NPV is positive for both discount rates and has an internal rate of return (IRR) of 5.42%.

4.6.3 Business case

Table 15 below shows the computation of the NPV of a reduction in distribution losses from the perspective of different sectors, based on the investment costs of Table 14 and benefits of Table 13 Table 15 reveals a negative discount rate for investing in a reduction in distribution losses solely from the perspective of the hydropower sector. The NPV from the public water sector (PWS) perspective is dependent on the discount rate. Below or above 2.72% will generate a positive or negative NPV respectively. From a multi-sector perspective, the NPV is positive for both discount rates since the IRR amounts to 5.42%.

Table 15 NPV of reducing distribution losses for different sectors in millions (US$)

Hydro-sector NPV (2%)	**-146.31**	PWS-sector NPV (2%)	**25.91**	Multi-sector NPV (2%)	**133.64**
Hydro-sector NPV (5%)	-179.89	**PWS-sector NPV(5%)**	-61.68	**Multi-sector NPV (5%)**	12.27
Hydro-sector IRR	-3.35%	**PWS-sector IRR**	2.72%	**Multi-sector IRR**	5.42%

This result illustrates that the business case of an adaptation measure can be positively influenced by taking into account the effects related to other sectors. For a 5% discount rate, the NPV of benefits is 73.48 and 191.69 million US$ for the hydro- and PWS-sector respectively. Given the costs of 253.37 million US$, no sector would be interested in investing in this measure due to a negative return. However, combining both benefits gives a positive NPV of 12.27 million US$. Therefore, distributing costs in such a manner that the NPV remains positive for both parties, i.e. costs <191.69 million US$ and <73.48 million US$ for the hydro- and PWS sector respectively, totaling at least 253.37, would imply a profitable business case.

Table 15illustrates that an unviable financing scheme for a single-sector investment can be turned viable by including payments from other sectors based on the share of benefits received by that sector. This can facilitate investment in adaptation, potentially improving the response to the future adaptation burden.

Increasing investment in adaptation measures in Ethiopia is needed in Ethiopia. For example, Bosello et al. (2011) indicate that the largest share of the global adaptation burden will be carried by developing countries. Besides that, the AfDB (2011) states that “Africa is arguably the most vulnerable region in the world to the impacts of climate change” (p.2).

For Africa, adaptation costs are estimated between 20-30 billion US$ per annum over the next 10 to 20 years. In 2011, only 350 million US$ had been allocated to spending on adaptation in Africa. The remaining financing gap is characterised as the adaptation deficit. Scarce funding opportunities induce a quest for adaptation solutions that maximize benefits and minimize costs (ECA, 2009). Multi-sectoral financing arrangements can help closing this gap.

4.7 Trade-offs in the water-energy-food nexus

In the case study presented presented in the previous section the Ribasim-Tiam models were employed to analyse the interdependencies between the two sectors at the national level in Ethiopia and to identify potential trade-offs and synergies. Two scenarios were developed to analyse whether the water sector can meet the rapidly growing demand for water for hydro electricity production: the baseline scenario for which no far reaching climate policy is assumed; and the RCP2.6 scenario which assumes a stringent climate policy in which the likelihood is high that the global average atmospheric temperature increase stays below 2 degrees Celsius.

The model analysis revealed that as a result of high population and economic growth rates, the electricity demand in the baseline scenario will grow to a level of approximately 66.7 GWh in 2050. Under the RCP2.6 scenario electricity demand will even further increase to a level of 86.8 GWh in the same year. The analysis showed that the amount of water needed to meet this high level of demand can be supplied without compromising water claims from other users such as irrigation and domestic water use.

This is true irrespective of possible negative hydrological impacts as a result of climate change induced decreased average precipitation nation-wide. Whether the Ethiopian government should pursue its ambitious hydro power development plan however also depends on environmental, geopolitical and social factors that are not included in this quantitative analysis. The main conclusion which can be drawn from the Tiam-Ribasim analysis is that at the national level future water availability will not impose a constraint on future water demand for hydropower production and other water use categories. However, at the regional level the situation could be very different with local shortages occurring in regions with low rainfall. Also rainfall variability is expected to increase due to climate change.

The energy analysis conducted with the Tiam model also provided projections for the amount of biomass (firewood for households and biomass for electricity production) needed in 2050. In the RCP2.6 scenario the demand for biomass is expected to increase from 1.1 EJ in the base year 2010 to 1.9 EJ in 2050. This is equal to 64.7 million ton and 112 million ton wood per year for 2010 and 2050, respectively. Subsequent analysis with the Water-limited Crop model model reveals that, assuming a sustainable yield of 10m3 per ha, 19.3 million ha of forest land is needed in 2050 to be able to produce this amount of wood in a sustainable way. Currently available forest area in Ethiopia is 12.3 million ha so clearly there is a trade-off between land use and energy.

The amount of water required to produce the required amount of biomass is estimated to be 6,210 million m^3 per year. Based on a forest area of 12.3 million ha, this amount of water would be equal to some 500 mm rainfall per year. The highest average annual rainfall of over 2,400 mm is in the south-western highlands of the Oromia Region. The lowest amount of rainfall of about 600 mm is in the north in areas bordering Eritrea, and it drops to less than 100 mm in the north-east in the Afar. Therefore, in most regions rainfall will be enough to produce the required amount of biomass and therefore no competition is expected in Ethiopia between the water sector and forest land.

Finally, the model exercise shows that there still is ample scope to improve food (maize) production necessary to feed the fast growing population in Ethiopia which will reach 145 million in 2050. More importantly, this food production growth will not need considerable amounts of water and therefore is not expected to constrain water demands from other users.

In summary, the quantitative analysis using the Tiam-Ribasim-Water-limited Crop model set shows that at the national level in Ethiopia the only significant trade- off concerns the biomass production(land use) needed for the energy sector. Table 16 presents an overview of the analysed interactions.

Table 16 Critical links between the water-energy and food sectors at the national level in Ethiopia

	Water	Energy	Food/landuse
Water	X	not critical	not critical
Energy	not critical	X	not critical
Food/land use	not critical	critical	X

Ethiopia is one of the largest countries of Sub-Sahara Africa with large differences among the various regions in rainfall amount, soil quality, topography, altitude, water hydrology, energy resources and demographic factors. This means that the conclusions drawn at the national level may be unsuitable at the regional level. In fact, the RIBASIM analysis for the Blue Nile area revealed that local water shortages will occur and can lead to conflicting claims for water use by different water users. To analyse more in detail the WEF nexus in a particular region, a second case study was conducted in the Humera region in Northern Ethiopia. The methodology and findings of the Humera case study are presented in a separate report[15].

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[15] Report on the Nexus Humera case study in Ethiopia

5. Towards the solution: conclusions from the Nexus analysis

This final chapter aims to summarize the main findings of the research results presented in this report and to draw conclusions and recommendations as to how the trade-offs between the water, energy and food sectors can become synergies. This provides the basis for addressing the criticism on the nexus approach expressed in the literature. Finally, an evaluation of the conceptual modelling framework is presented along with research gaps that still need to be dealt with.

5.1 Introduction

The Bonn 2011 nexus Conference created a strong momentum behind the water, energy and food security nexus concept that aims to integrate management and governance of these resources across the three sectors. The rapidly increasing demand for water, energy and food calls for a more cross sectoral approach that takes into account the interdependencies between these sectors. This can significantly improve the efficiency and effectiveness of policy measures and can contribute to achieving more development with less resources and environmental pressure.

Six years after the Bonn nexus Conference, the nexus philosophy has gained more significance and is now higher on the political agenda. The climate dimension has been brought in to the original WEF nexus framework and the adoption of the Sustainable Development Goals has broadened the scope to include other relevant sectors such as health, ecosystems, infrastructure and industrialization, sustainable consumption and production and poverty.

A considerable amount of nexus-related research has been conducted during the past six years, mostly focusing on the development of the WEF nexus concept. Only few studies have been published so far that aim to quantify the interdependencies between the WEF sectors and to identify and evaluate potential trade-offs and synergies. The present study aims to partly fill this gap by applying the WEF framework to case study Ethiopia.

The literature review presented in Chapter 2 provides the basis from which the conceptual and methodological framework for the WEF nexus could be developed. This framework is presented in chapter 3 and entails an in depth analysis of the interdependencies between the WEF sectors, a definition of the system boundaries and the formulation of the key steps of the nexus approach.

In Chapter 4 the nexus conceptual and modelling framework has been applied to Ethiopia. Firstly, based on the methodological approached developed we assessed in depth the key development challenges of Ethiopia, its policy agenda and how this translate into important intersectoral claims now and in the future, as well as how these will be affected by Climate Change. Departing from the key claims identified we zoom and making use of the trade-offs - already identified through the literature review (Chapter 2) and summarized as a matrix (Annex C) and depicted as Causal Loop Diagrams (Annex D)- we analysed in depth critical linkages and interdependencies between the three sectors, the specific trade-offs and dilemmas faced by Ethiopia and potential points of leverage and synergies that should be taken into consideration in the formulation of Climate Smart Strategies.

Secondly Ribasim/Tiam/Water-limited crop model set was used to quantify the interactions between the sectors and to evaluate long- term integrated demand and supply strategies across the WEF sectors. Until the present study these sector models were used by the consortium partners to analyse sector specific strategies. In the present study these models have been soft linked to create a powerful model package that enables a detailed analysis of the consequences of policy measures taken in one sector on the other sectors. Last but not least, an economic appraisal of alternative adaptation options to solve water-energy trade-offs in the face of Climate Change is undertaken.

The complexity of the water, energy, food nexus approach makes stakeholder participation essential. Engaging the key stakeholders from the onset greatly enhances the quality and legitimacy of the model results and also improves the chance of informing decision making. Through raising awareness and creating stakeholder buy –in the implementation of the proposed changes through concrete projects can be facilitated. In Chapter 4 the stakeholder analysis forms a key component of the nexus framework.

The analysis conducted at the national level of Ethiopia provided deeper insights into the extent to which water, energy and food resource availability is sufficient to meet long-term demand for these resources. However, Ethiopia is among the largest countries by area in sub-sahara Africa and the regional conditions could be very different from the national totals. Therefore, as a separate activity, a second case study on the WEF nexus has been conducted in the Humera district in northern Ethiopia. The results of this regional case study are presented in a separate document.[16]

5.2 Most significant trade-offs and leverage points

By applying the methodological and modelling Nexus framework to Ethiopia as explained above, we can come to a list of more important trade-offs faced by Ethiopia in their goal to achieve sustainable economic development in the face of Climate Change. Taking these dilemma's as central in our analysis of leverage points we have also identified relevant Climate Smart Solutions and Strategies for the country. These findings are summarized below:

5.2.1 Water and food security

Water used for agriculture cannot be used for domestic purposes (WASH). Ethiopia's policy objective is to expand crop production by 50% and nearly double the area of land equipped with irrigation schemes. Irrigation schemes allow for a more evenly distributed consumption of water resources, leading to a higher water footprint.

Furthermore, a surge in livestock is expected to meet higher meat demand, which is notorious for its high water footprint. Extracting additional water resources for agriculture will have consequences for the overall surface and groundwater balance. Therefore, system-wide cascading

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[16] Report on the Nexus Humera case study in Ethiopia.

effects of water use in one location need to take into account other beneficiaries of water resources.

Agriculture is the largest driver of deforestation- which can lead to deterioration in groundwater recharge capacity and water quality; threatening in the long term water and food security itself. Population growth and growth in food demand is expected to drive an increase in total agricultural land which leads to an increase in the annual deforestation rate, a reduction of natural ecosystem and a degradation of ecosystems health. Poor ecosystem health of river systems translates into reduced river discharges and yearly water supply, and therefore higher water stress levels.

A way to limit the expansion of agricultural land would be to increase the yield per crop field. However this would require the intensive use of pesticides and fertilisers and impact water quality through run-off and nitrate pollution. Moreover, domestic fertilizer production expected to double by 2020, is also expected to increase significantly water demand.

Important mechanisms that drive system performance are the two important reinforcing loops with Ecosystems Health as departure point could become vicious cycles that deteriorate exponentially the water stress challenge and/or virtuous cycles that lead to an exponential increase of water supply. Ecosystem Health affects river discharge levels and water quality, both of which define water supply. Limited water supply and stress often means that environmental flows are not ensured and that Ecosystem Health is further deteriorated. Ecosystem Health not only plays a role in water supply within normal conditions but also contributes to the resilience of landscapes and the reduction of economic and crop production losses in extreme dry/wet years. This seems all in all to be a leverage point of the system. Therefore is not surprising that reduction of deforestation rates is the focus of the work of many NGOs and governmental campaigns around the world.

Technological and policy measures that could trigger improvements in food production, without activating these negative side effects on water security. Options are: a) Conservation and Climate Smart Agriculture techniques that while increasing average yield, limit or revert deforestation rates and reduce production losses due to extreme weather events. b) Improvements in soil nutrient levels, seed quality and/or irrigation systems that impact positively food production by increasing average yield and/or water productivity without affecting water quality. And last but not least, reforms to agricultural and water rights that create the incentives for farmers to invest in more efficient irrigation systems and other measures to reduce evotranspiration.

5.2.2 Water and energy security

Hydropower production requires large volumes of water to be stored. Water consumed through reservoir evaporation cannot be used elsewhere. Furthermore, water quality is affected due to higher temperatures and an altered sediment regime, which can result in levels unfit for drinking.

An important aspect between these two sectors relates to the impact of increasing share of renewables on water and food security: the impact of large dams. A significant increase in hydropower generation aiming at a higher share of renewables in the total energy mix and an increase in access to modern energy sources; can be detrimental for the achievement of other SDG's if the choice is made for larger size dams. Large size dams given the large extensions of land they require for their construction, as well as the disturbances they create on rivers; may have considerable negative effects on: a) Forest cover – due to upstream deforestation; b) percentage of children malnourished due to both a loss in annual crop production through agricultural land and annual fish production through a reduction of fish migration flows. c) Last but not least, the disturbance of river ecosystems results often in a significant increase of waterborne diseases. Risk mitigation measures could be: implementation of multi-use reservoirs and landscape and ecosystem management measures.

Last but not least, continued dependence on traditional biomass energy resources will increase demand due to population growth. Sustaining existing forests and additional on-farm production of biomass resources leads to a higher water footprint of around 500 mm rainfall per year (section 4.7), which can be met by precipitation levels in various regions in Ethiopia. However, a trade-off arises when this water use conflicts with other demands. Unsustainable yield from existing forests leads to deforestation, potentially impeding water quality and recharge.

Synergies can be achieved through the (further) development of Ethiopia's vast potential of renewable energy resources, in particular solar energy, biomass and geothermal energy. This would positively affect the energy sector (diversification of supply), the food sector (electricity supply for the agriculture sector) and the water sector(less hydro power production needed thus water can be used for other users).

5.2.3 Energy and food security

To finalize important trade-offs between energy and food security are:

- Land determined for on-farm biofuel production cannot be used for agricultural purposes and vice-versa. Quantative analysis revealed that for sustainable yield levels an additional 7 million ha of land needed for wood production in 2050 (section 4.7).
- Dung used for cooking cannot be used for fertilization and vice-versa.
- Agricultural modernisation and development of an agro-industrial sector drive up energy demand, leading to conflict with other energy users.

Potential measures to create synergy between energy and food security objectives are:

Solar powered water pumping for irrigation can improve agricultural yields and is considered as a basic strategy to alleviate poverty and improve food security. Modern irrigation systems are based on diesel or electric driven water pumping systems. However, solar powered water pumping is becoming increasingly interesting because the sharp decline in costs of solar PV. Solar pumping replaces diesel and/or electricity and thus may reduce CO_2 emissions. .

Biofuel production from non-food crops. Currently, Ethiopia has to import all its oil requirements which account for more than 80% of its export earnings. The country has high potential for biofuel production. To reduce the financial burden on the national budget and create employment and income the government is pursuing a biofuel development strategy focused on the production of ethanol from sugar beet and sugar cane and the production of biodiesel from Jatropha and castor bean plants Despite its high potential, currently the biofuel sector is still underdeveloped. This is mainly due to lack of a conducive regulatory framework and high production costs. However, the growing concerns about climate change and the rapidly increasing global energy demand lead to renewed interest in biofuels that are derived from renewable sources. Non-food biofuel feedstock may create synergies between energy and food security objectives provided that the cultivation of land for energy crops does not lead to completion for cropland. .

Introduction of afforestation and deforestation policies. To combat the high deforestation rate the Ethiopian government has developed and implemented afforestation and reforestation policies. These policies involve farm land and community tree planting programmes and rehabilitation and creation of productive forest land that aim to improve local livelihoods, to reduce total water consumption through evapotranspiration and to increase fuelwood availability.

These measures create synergies between the energy (increase in wood supply), water (reduced evaporation) and food(reduced erosion) security objectives.

Accelerated introduction of improved cook stoves: current wood demand in Ethiopia is unsustainable and results in high deforestation rates. The accelerated dissemination of improved cook stoves among especially rural households aims to address this problem by using wood more efficiently. This could reduce deforestation and land degradation but would also positively affect indoor air pollution which causes adverse health effects. This therefore is a good example of creating synergy between the energy (reduced demand for woodfuel), land use (reduced land degradation) and health (reduced indoor air pollution) objectives.

5.3 How to create synergies between the WEF sectors: reaching WEF security

The sections above illustrate that expanding the size of one sector can generate a trade-off due to multiple sectors being dependent on the same resource. Therefore, achieving a particular sectoral policy goal can be at the detriment of another. The significance and size of a trade-off depends on the availability of the resource(s) for which a conflicting demand has arisen.

Integrated inter-sectoral policy making is required in order to detect trade-offs and minimise their materialization. This does not imply that trade-offs can be prevented, since competing demands are inherent to the fixed endowment of the overall WEF-nexus, i.e. no additional land, water and energy sources can be created within the confines of Ethiopia. However, increasing the efficiency of resource use needed for reaching one policy goal can free up resources for another one.

Furthermore, inter-sectoral interdependencies as illustrated by the CLDs in Appendix D should be taken into account when policy goals are determined. A single-sectoral approach that aims to maximise the development of each sector leads to disregard for system-wide consequences of resource use implied by reaching a policy target.

Furthermore, the allocation of limited (public) resources through policy should be based on the marginal benefits generated by each policy target. For example, the societal benefit of allocating water to meat production might be lower than providing WASH access for subsistence.

The multi-scale approach we have developed and tested for the Ethiopia for analysis of nexus trade-off can be used either by donors, multilaterals to analyse and test at national and local level whether certain sectoral investments being planned are Climate Smart and advance the synergetic achievement of water-food and energy related SDG’s. The methodological approach developed and illustrated for the case of Ethiopia can also support governments in the generation of alternative solutions and changes in the design of these projects so that future nexus stresses and vulnerabilities are reduced to a minimum.

5.4 Addressing the criticism on the nexus approach

Based on our analysis of the water-energy-food nexus we can reflect in the criticisms raised in section 2.2 and explain our we have dealt with them through the design of our conceptual and modelling framework.

Is the basic problem, the ‘scarcity of resources’ not a political issue which cannot be solved in a technological or managerial way?

We deal with this criticism by using the leverage points of Meadows (2007) which explicitly acknowledge the limitation of technological solutions alone and encourage the identification of alternative Climate Smart Strategies that make use of more powerful leverage points such as: the structure of information flows (who does and does not have access to information), The rules of the system (such as incentives, punishments, constraints) or the power to add, change, evolve, or self-organize system structure.

It should be acknowledge that to apply these more powerful and structural solutions to the nexus problem will remain a significant institutional challenge, as it may require a challenge of the status quo and current allocation of power. These aspects were outside the scope of our study. We have developed an approach for the nexus that focus on identification of problems and trade-off and does not go in detail on the strategies for implementation. However, current power imbalances may limit even the process of identification and framing of nexus problems,

Is the nexus approach not too optimistic about investment, innovation and ingenuity?
The criticism here is that the nexus promotors follow an optimistic view where limits can be overcome through investment, innovation and ingenuity, driven by even more sophisticated technologies. This criticism may be true to a certain extent, but (also in developing countries) there is still much space and need for implementation of new technologies, innovations and investments. Downplaying environmental externalities, such as biodiversity and climate change are, however, serious threats.

We deal with this criticism by adopting an ample approach in the study of the nexus , which places as central issue the achievement of the SGD's and in this way the situation of the most vulnerable groups of society.

Are we not hiding the bigger debate?
It may be true to a certain extent that the nexus is hiding the bigger debate about resource inequality. However, when you take the principles and areas of opportunities as formulated in Hoff (2011) – see above - seriously, the outcome should not differ much from the situation critical scientists such as Allouche et al. (2015) would wish. The practical situation is hard: there are differences in (economic) power, knowledge, organizations, networks and lack of learning and communication. This demands a good strategy and stubborn but flexible efforts to implement a nexus approach.

We partly deal with this criticism by applying the leverage points perspective, which explicitly acknowledge that far more effective than a mere change in parameters (e.g. by technological solutions) are measures that a) introduce a change in the rules of the system (such as incentives, punishments, constraints); b) change existing power to add and change hold by stakeholders and allow for the system to evolve or self-organize itself in a more organic way; or even changes that enable societies to transcend present paradigms. Again as noted above, current power imbalances may limit this process of identification of more effective leverage points.

Is integration of the food, water, energy and climate change sectors really possible? How can we assure integration of sectors on an equal footing?
Hoff (2011) recognizes that "there is no blueprint for overcoming institutional disconnect and power imbalances between sectors, e.g. blue and green water generally falling under different ministries, or energy often having a stronger voice than water or environment, indicating that the nexus may not be traded-off equally. "

What seems to be new in the nexus concept is the more active interest and involvement of the private sector. In the business world, the awareness is growing that resources are becoming scarcer and that problems of scarcity of resources should be considered from a plural perspective. In many local and regional multi-stakeholder processes for example to promote governance of natural resources (water, forests etc.) in a certain region or area, the private sector, although an important stakeholder with considerable influence on the local situation, was absent. In the nexus approach the private sector shows interest and commitment. This is an important and positive development, an opportunity.

We deal with this point by undertaking a stakeholder analysis and liking the policy objectives and outcomes of interest with the responsible government agency; and going further into analysing and pointing out the conflicts and trade-offs between these policy goals. Also further in the local case study realized in Humera, we deal with this criticism by making use of collaborative modelling techniques, such as the Nexus game; and designing the process of interaction with stakeholders during our first and second mission in such a way that engagement and collaboration between these different government authorities and the breaking of silos is encouraged.

5.5 Methodological findings

5.5.1 Operationalization of the methodological framework

Adopting a systems analysis approach for analysing the WEF-nexus reveals potential conflicts in achieving multiple development objectives simultaneously, by showing bottlenecks in terms of resource claims and linking it to dependent policy objectives. Furthermore, adopting the system analysis approach allows one to distinguish between future constraining conditions due to climatic or socio-economic drivers, which can influence the desired adaptation approach, e.g. by reacting to climate pressures or by steering towards a more climate-resilient socio-economic development path.

By undertaking a in depth analysis of the WEF system, key interpedencies between the water-food – energy sectors we enable the explicit formulation of key policy dilemmas, which helps to elucidate the specific conflicting points and trade-offs faced by a country in their endavour to achieve food, water and energy security along with the desired economic growth that is key for the achievement of other SDG’s . This process also helps to formulate problem definitions that are clear and helpful for the search of climate smart strategies; strategies that are effective in the long term and deal with the root causes of Ethiopia development and environmental challenges and that have the potential to solve the trade-offs or to create additional synergies within the nexus.

5.5.2 Quantitative analysis by soft-linking water and energy models

The results obtained through our cross-validation of TIAM-ECN and RIBASIM model outputs show that we have identified an approach that can be used for the multi-sectoral assessment of energy and water policies and for the inspection of the compatibility between them. Yet our analysis has focused mainly on the quantitative aspects of hydropower development and water resources management. The actual success of hydropower expansion at the national level against concomitant growth of agricultural and domestic water needs will not only be dependent on technical feasibility, but likewise on the technical and managerial capacity of operators to ensure an optimal distribution of resources across users and time. It will also depend on the government's ability to ensure the institutional support and financing needed for maintaining the water supply system.

One of the primary aims of this study was to test the possibility of soft-linking energy and water sector modelling tools so as to provide practical instruments for analysis of energy-water nexus challenges and constraints. Through a number of joint input assumptions we enabled the results of our models to be contrasted to each other, even while they followed distinct approaches.

By soft-linking these two models we determine what the cost-optimal level of hydropower generation could be under baseline and stringent climate change control regimes, and investigate whether these production levels are realistic from a hydrological and water balance point of view and may be imperilled by the adverse impacts on water supply from average climate change effects as well as expected increases in water demand from domestic and agricultural sectors.

Through our two approaches we project a high level of hydropower generation in Ethiopia: between 71 and 87 TWh/yr by 2050 in a stringent climate change control scenario in which the country contributes substantially to global efforts to reach the 2 C target fixed in the Paris Agreement (COP-21, 2015). On the basis of the dimensions addressed by our two models energy system costs, national hydrological features and average climate factors one may be tempted to argue that it makes sense for Ethiopia to pursue its current ambitious hydropower development plan. Other issues, however, that are beyond our confined scope need to be considered for such reasoning to hold.

5.5.3 Economic analysis of multisector adaptation investments

The vulnerability framework has proven to be a useful aid in conceptualizing the temporal evolution of vulnerability. By categorizing potential impact according to driving (exposure, sensitivity) and mitigating (adaptive capacity) factors it is possible to establish a baseline conceptualization describing the interaction between a system and climate change Subsequently, practical detail regarding the dynamics of vulnerability development can be added by linking economic, demographic and meteorological parameters to the categorizations. For example, economic growth leads to energy demand, which spurs hydropower development, representing an increase in exposure.

Transforming the arrangement of categorizations and accompanying parameters into a functional form allows for distinguishing between different options aimed at mitigating future vulnerability. Boiling down the dynamics of climate change vulnerability to equation (16) below allows one to envision the objective and possible pathways to achieve it. The objective is to reduce vulnerability trough adaptation (y) compared to the baseline situation (x), i.e. when $Impact_y > 0$, according to equation 17.

$$Vulnerability_{x,y} = f(Adaptive\ capacity_{x,y,z}, Exposure_{x,y,z}, Sensitivity) \quad (16)$$

$$Impact_y = f(Vulnerability_x) - f(Vulnerability_y) \quad (17)$$

$$Impact_y = f(Vulnerability_x) - f\left(Vulnerability_y\right) \pm costs/benefits\ other\ sectors \quad (18)$$

Besides that, by expanding equation (16) with the effects in other sectors (see equation (18)) and integrating it into an NPV analysis, one can demonstrate what ‘taking the WEF nexus into account’ means for investment planning in climate change adaptation. Augmenting the business case of an adaptation measure with effects from other sectors can improve overall financial viability when vulnerability to climate change decreases basin-wide. Distributing investment costs proportional to expected benefits can transcend sector borders and thereby stimulate implementation of adaptation measures.

5.6 Research and innovation gaps

The most important research and innovations gaps identified are the following.

Firstly, our nexus approach guide the identification of trade-offs between sectors; for which solution you will require collaboration between different sectors. The key question that remains is how, once you have identified the problem and the needs for collaboration, you can effectively drive these sectors to work together. Important governance questions are how to create the conditions under which cross-sector coordination and collaboration takes place. Which fact-base and incentives are required to make these collaboration platforms evolve from “discussion platforms” to an implementing workgroup with a clear work plan and procedures for resolution of these trade-offs.

In addition to the technical aspects of the WEF nexus, the institutional nexus frame work is equally important. The institutional structure should be built in such a way that it can support the adoption of technical nexus solutions. Cross-sectoral coordination and collaboration is essential and should be fostered through suitable institutional structures. This however is not always evident because of the imbalance in political power between the sectors. More research therefore is needed to analyze the institutional aspects of the nexus approach to ensure effective implementation of the nexus solutions.

Secondly, further research is required on how to “define the nexus” in a specific context. A sound analysis is needed to draw a clear line about what needs to remain and dealt by sectoral agencies, and what needs to be managed in nexus collaboration. In our research we have advanced this goal by defining a method to identify the most important intersectoral claims. Nevertheless to bring this method towards a mature structured process that is universally applicable for the definition of this context-specific balance of issues to deal with by the silos versus issues that require nexus collaboration will require the application of the methodology in many more cases in different regions and at different scales.

Based in our findings we advise that in the definition of this balance one does not limit itself to the World-Energy-Food nexus, but following a problem oriented search one defines what needs to be dealt with in collaboration and what nots. This may translate in some places to only water-energy, while in others may even require the consideration of Land and Marine Ecosystems.

Although the water-energy food security nexus currently forms the core of the nexus research, interactions with other sectors may also be important. An obvious example is climate change which in interlinked to the WEF sectors through changing weather patterns that could result in floods and droughts. But other sectors such as health, sustainable consumption and production, infrastructure and industrialization and cities may also affect the WEF sectors. Further research is needed to investigate if and under what conditions critical links exist beyond the WEF. This is especially relevant for the SDG framework which comprises 17 goals and 169 related targets that have many interconnections. To identify those links that really affect the system helps to formulate integrated policies that reduce the trade-offs and create synergies

Thirdly, another related methodological question that remains is on how to decide which approach to use when and at which institutional and geographical scale. More specifically how should the landscape and the IWRM approaches collaborate and/or link with the nexus approach. In our research the Nexus approach turned out effective to identify trade-offs and solution directions at the national and regional level; but a further detailing of these solutions and their implementation requires the consideration of more institutional and governance issues such as water rights. It may be that IWRM and the landscape approach are better equipped to deal with these issues given their bottom-up nature; or that these issues need to be solved per sector. Again by applying the nexus methodology developed in many more cases one could test these boundaries.

Fourthly, should the approach developed and tested at the local scale (Humera) for the analysis of important investments – in our case a large Agro-Industry park- become a standard part of pre-feasibility studies? How identifying future bottlenecks in terms of resource use triggered by the investment project early in the process could inform and serve a better project design and the definition of the management and commercial business cases of these investments. In other words, how this analysis could inform and inspire the design of alternative business models and structuring of deals in such a way that these trade-offs are internalized and managed by a single public or private entity.

Last but not least, we recommend further work on the sharpening of analytical and modelling tools for the identification, reporting and evaluation of trade-offs. Whether we go for a single integrated model or soft linking of sectoral models; two key constraints for the quantification of these trade-offs are: availability of good quality data and of standards definitions and metrics common to the sectors covered by the nexus. Further work on these two constraints is essential to advance in the analysis and solution of nexus challenges.

The modelling package, comprising the Ribasim/Tiam/water-limited yield models, proved a very useful tool to analyse the implications of an intervention in one sector for the other sectors. However, the three models were originally developed to mathematically describe one particular sector only and were not designed to also take into account the interactions with the other sectors. This means that for the present study the three models were 'soft-linked' to analyse the nexus implications; output from one model was manually entered as input for the other models. a pending question given the two key constraints defined above is if these models could be physically integrated so that intervention in one sector is automatically taken into account in the other sector. And how this integration could enable the identification of optimal solutions across the three sectors simultaneously.

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Appendices

Appendix A: SDG targets and proxies

Appendix B: production processes of each sector

Appendix C: Matrix, Food, Water, water, Energy and Climate Change

Appendix D: Causal loop diagrams of key trade-offs and synergies

Appendix E: Identifying leverage points

Appendix F: Results from the Group Model Building sessions of them Nexus research team

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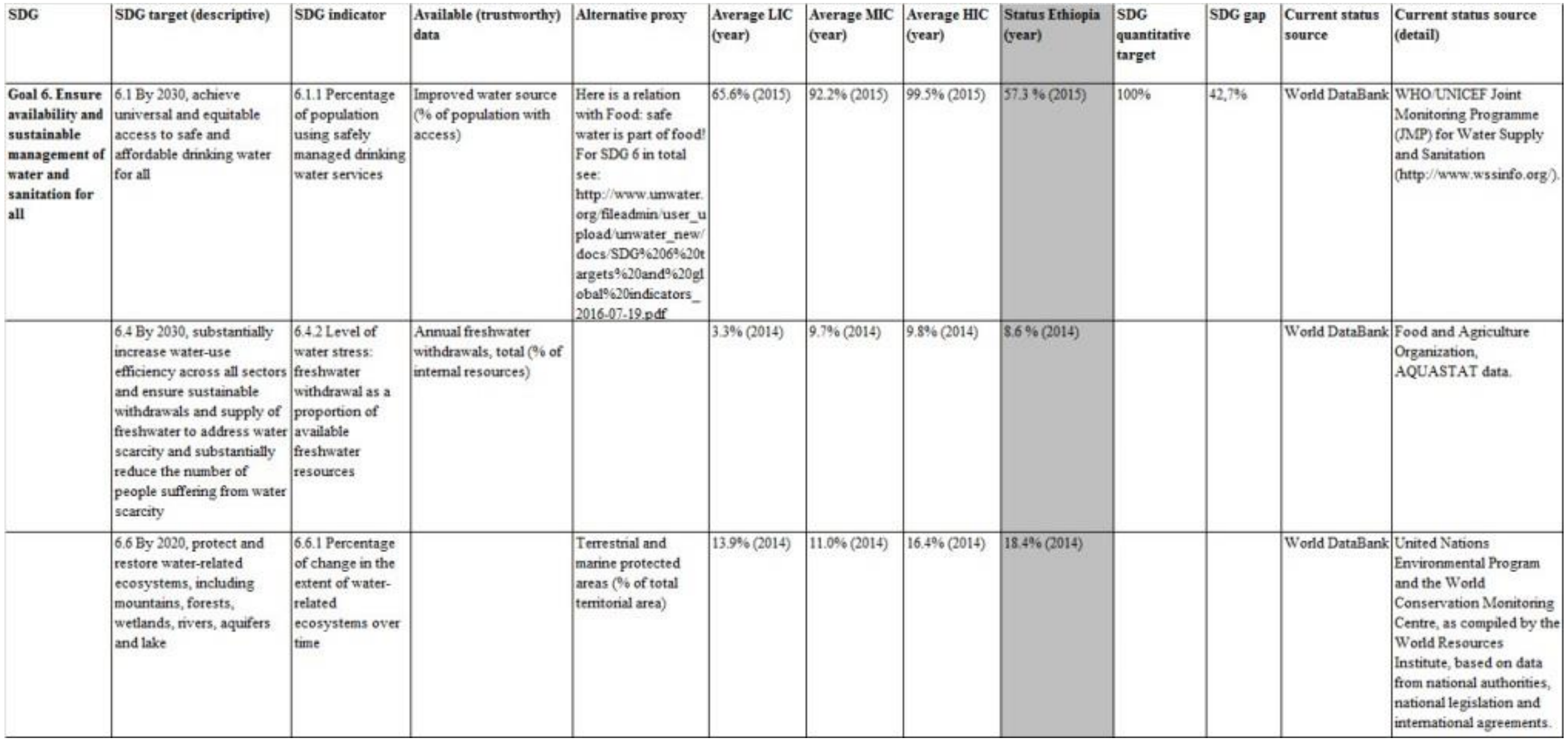
Appendix A: SDG targets and proxies



SDG	SDG target (descriptive)	SDG indicator	Available (trustworthy) data	Alternative proxy	Average LIC (year)	Average MIC (year)	Average HIC (year)	Status Ethiopia (year)	SDG quantitative target	SDG gap	Current status source	Current status source (detail)
Goal 6. Ensure availability and sustainable management of water and sanitation for all	6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	6.1.1 Percentage of population using safely managed drinking water services	Improved water source (% of population with access)	Here is a relation with Food: safe water is part of food! For SDG 6 in total see: http://www.unwater.org/fileadmin/user_upload/unwater_new/docs/SDG%206%20targets%20and%20global%20indicators_2016-07-19.pdf	65.6% (2015)	92.2% (2015)	99.5% (2015)	57.3 % (2015)	100%	42,7%	World DataBank	WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply and Sanitation (http://www.wssinfo.org/).
	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Annual freshwater withdrawals, total (% of internal resources)		3.3% (2014)	9.7% (2014)	9.8% (2014)	8.6 % (2014)			World DataBank	Food and Agriculture Organization, AQUASTAT data.
	6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lake	6.6.1 Percentage of change in the extent of water-related ecosystems over time		Terrestrial and marine protected areas (% of total territorial area)	13.9% (2014)	11.0% (2014)	16.4% (2014)	18.4% (2014)			World DataBank	United Nations Environmental Program and the World Conservation Monitoring Centre, as compiled by the World Resources Institute, based on data from national authorities, national legislation and international agreements.

For Illustration purpose only Goal 6 is depicted, but all goals selected for the framework are included in the enclosed excel file

Appendix B: production processes of each sector requiring input from other sectors

WATER demand and supply

Water Demand *(ranked high-low)*	Water Production and Supply *Availability (ranked high-low)*
1. Agriculture 2. Population 3. Industry 4. Ecosystems	1. Surface water extraction - River discharge - Drainage - Storage volume 2. Groundwater extraction - Pumping capacity - Storage volume - Aquifer recharge 3. Re-use (waste water treatment) - Capacity of waste water treatment 4. Rain harvesting (rain-fed) - Precipitation rate 5. Desalinisation - Capacity of desalinisation

ENERGY production – WATER demand

Energy Production and Supply *(ranked high-low)*	Water needed for
1. Hydropower generation 2. Energy plants (gas, coal, nuclear, ..) 3. Energy drilling and fracking 4. Solar energy plants 5. Biofuel production	1. Processing 2. Cooling

WATER production –ENERGY demand

Water Production and Supply *(ranked high-low)*	Energy needed for
1. Surface water 2. Groundwater extraction 3. Re-use (waste water treatment) 4. Rain harvesting 5. Desalinisation	1. Pumping 2. Transport / distribution 3. Filtering / waste water treatment 4. Desalinisation production

ENERGY production – FOOD demand

Energy Production and Supply *(ranked high-low)*	Food needed for
Bio fuel	- Processing
	- Land required for biofuel crop production
	- Land required for energy generation installations: solar, wind

FOOD demand and supply

Food Demand *(ranked high-low)*	Food Production and Supply -> *Availability (ranked high-low)*
By population - Total food demand - Demand for high quality crops	- Agricultural areas - Green houses - Aquaculture - Livestock - Tree crops - Grassland - Fisheries - Hunting

ENERGY demand and supply

Energy Demand *(ranked high-low)*	Energy Production and Supply *-> Availability (ranked high-low)*
1. Households 2. Industry 3. Transport 4. Commercial 5. Other sectors	1. Fossil Energy plants (gas, coal,.) 2. Hydropower generation 3. Solar energy plants 4. Biofuel production (incl. biodigester) 5. Wind energy 6. geothermal energy 7. wave energy 8. nuclear energy

FOOD production - WATER demand

Food Production and Supply *(ranked high-low)*	Water needed for
1. Agriculture	1. Irrigation 2. Fertilizers production 3. Processing 4. Water for animals 5. Water as habitat for fish

FOOD production - ENERGY demand

Food Production and Supply *(ranked high-low)*	**Energy needed for**
1. Agriculture	1. Food production harvesting 2. Processing / packaging 3. Transport 4. Storage and cooling 5. Cooking of food

Appendix C: Matrix Food, Water, Energy and Climate Change

Sources:

- Bellfield, H. 2015. Water, energy and food security nexus in Latin America and the Caribbean. Global Canopy programme, 57 pp. ;
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  These trade-offs have been clustered and represented graphically by a number of causal loop diagrams (appendix D), in which the numbers given to each trade-off mentioned in this table are referred to so as to make the connection easier for the reader.

Water and energy (water for energy)

Trade-offs	Additional impact of Climate change on the trade-off	Possible impact of the trade-off on climate change	Possible impact of trade-off on ecosystems, or relation with natural ecosystems	Synergies or measures to decrease the mentioned trade-off
(1) Hydropower reservoirs can have significant evaporative losses. So the question is: Water use for generating hydropower versus the use for other purposes. Large hydropower dams are controversial because of potentially serious ecological and social damage	• Future drier conditions may increase competition for water and result in more periods of low hydro-energy production. • Drier conditions may increase evaporation of surface water.	• Emission of methane from (artificial) hydro-lakes/ reservoirs. Methane is a very strong greenhouse gas	• Hydropower lakes occupy land and lead to loss of ecosystems. • Possible water-borne diseases • Dam changes the river ecosystem and is an obstacle for fish migration. • Upstream the hydro dam, it is important to apply good landscape and ecosystem management in order to avoid erosion on the land and siltation in the lake.	• Coupled water-energy systems • Investing in infrastructure • Reforming subsidies • Land use and water use planning • environmental impact assessment (EIA and SEA), and measures also to limit evaporation. • Multi-use reservoirs. •
(2) Energy drilling (gaz, oi) and fracking: pollution of water (Niger Delta, Gulf of Mexico, etc.) changing water quality or temperature	• Climate change may result in even warmer water. Warmer, polluted water may be a bigger threat to health.	• Fossil fuel drilling and production continues the process of using fossil fuels and of emission of CO_2	Pollution of water and/or increased water temperature lead to (generally negative) changes in ecosystems	• environmental impact assessment (EIA and SEA), and measures • Land and water use planning • Energy policy which does not only focus on fossil fuels. • Use brackish or other marginal water • Increase transmission capacity
(3) Thermal and nuclear power plants: use of (much) cooling water which also results in heating of surface water.	• Warmer climate may make temperature of natural waters still higher. Elevated water and air temperatures reduce the efficiency of power plant generation. • Increased numerous and intense floods in areas close to energy plants can cause severe harm to	• Thermal power plants produce much CO_2	Increased water temperature lead to (generally negative) changes in water ecosystems	• Use cooling water for heating houses or other purposes. • Switch from water cooling to air cooling, or other techniques. Coastal power plants do not use fresh water. • Use of renewable energy; market wind-energy as zero-water, rather than just a low-carbon alternative. • Switching from wet to dry cooling at thermoelectric power plants

	power production and energy delivery infrastructure. Fuel transport by rail and barge may be interrupted more frequently. • Electricity transmission is less efficient with higher air temperatures, weakening the capacity of grid infrastructure. • More hot weather events (caused by climate change) may lead to soaring energy demand for air conditioners and to seasonal scarcity of water for cooling the power plants.			
(4) Recent switch to growing feedstock as first-generation biofuels, often with generous governmental subsidies, has an upward pressure on water use in agriculture. Biofuels are substantially more water intensive than fossil fuels.	• Climate change induced drought will increase competition between biofuel crops and other water users for clean sweet water • Climate change discussion may push biofuel crops even more • Higher CO2 in the air increases crop growth	First-generation biofuels were intended to diminish greenhouse gas emissions (by using less fossil fuels), but the debate about whether this is true, is fierce.	Biofuel production is also land-intensive. Cultivation of crops for biofuel leads to conversion of forests and other natural ecosystems to agricultural monocultures (e.g. oil palm plantations).	• Use only second-generation biofuels • Use sustainable sources of energy (solar, wind, etc.) • Plant biofuel producing crops on abandoned agricultural land (which is not competing for water with food production) – this solution has its limitations. • Only use crop residues for biofuel (when not used already for other purposes)
(5) In the value chain from raw materials (like oil, coal, gas and biofuels) to transformation into energy, much water is used.	• Climate change may cause more extreme events like droughts. In dry periods there may not be enough water to transform raw materials into energy	Fossil fuels produce much CO2	Use of extra water is often at the expense of natural ecosystems like wetlands and rivers.	• Integrated water policy • Water productivity in ethanol processing has increased by 30% in the first decade of the 21st century. • Recycling-reuse of this water
(6) The concentrated solar thermal plant, one form of solar energy	Climate change may cause more extreme events like droughts. In dry periods there		Use of extra water is often at the expense of natural	• Concentrated solar thermal plants should be planned in relation to a water policy

generation, uses relatively large quantities of water in relation to other renewable alternatives.	may not be enough water to provide this plant with water		ecosystems like wetlands and rivers.	

Water and energy (energy for water)

Trade-offs	**Additional impact of Climate change on the trade-off**	**Possible impact of the trade-off on climate change**	**Possible impact of trade-off on ecosystems, or relation with natural ecosystems**	**Synergies or measures to decrease the mentioned trade-off**
(7) Energy is used in the provision of water services. Energy is used for lifting, moving distributing and treating water. It is necessary for pumping water for domestic use, irrigation and/or water management. Energy used to deliver water over long distances or great elevations is very energy-intensive. Especially in rural areas energy provision may be scarce.	In drier conditions (caused by climate change) more water should be pumped up (from deeper depths). This costs more energy and may reduce the water table in an unsustainable way.	Using fossil energy increases carbon emissions.	• Using fossil energy increases pollutants in air and sometimes in water. These pollutants may enter ecosystems so that these produce less products (or polluted products) and less services. • To a certain extent natural ecosystems can purify polluted water.	• Use pumps which consume renewable energy • Groundwater supply, on average requires about 30% more electricity on a unit basis than does surface water. So use surface water if acceptable. • Use water as efficiently as possible (also final consumers) • Increase energy reliability by decreasing electricity gaps for pumping irrigation water (so you do not leave pumps on all the time). • By improving the productivity of rain fed agriculture, energy intensive irrigation can be limited or reduced. • New storage and conveyance of water to serve new demands • Watershed management
(8) Energy is used in treatment of wastewater		Using fossil energy increases carbon emissions.	Using fossil energy increases pollutants in air and sometimes in water.	• Energy recovery from wastewater can reduce the energy demand in the treatment plant, or even allow an excess of energy to the power grid. •
(9) Energy is used for desalinisation (50% in MENA region: Middle East and North Africa)	• Climate change causes a higher sea level, which results in more lands and waters with salinization problems.	Using fossil energy increases carbon emissions.	Using fossil energy increases pollutants in air and sometimes in water.	• Shift from fossil fuels to renewable energy for desalinisation. • Desalinisation of brackish water requires less energy than seawater desalinisation. Some regions have large reservoirs of brackish water. • Make agriculture (and other water using activities) more water efficient so that more fresh water remains and less salinization occurs.

Water and food security

Trade-offs	Additional impact of Climate change on the trade-off	Possible impact of the trade-off on climate change	Possible impact of trade-off on ecosystems, or relation with natural ecosystems	Synergies or measures to decrease the mentioned trade-off
(10) Food production is the largest user of water at the global level. Water for agriculture or (irrigation) is often at the expense of its use for domestic use (towns, cities, but also at household level in farms). To feed ourselves the world will need to double food production in the next 40 years to meet the projected demand (more people and more demanding diets). So even more water will be needed for agriculture.	• Future drier conditions may increase competition for water. It may lead to more tensions between city and rural area for water. • Longer drier periods because of climate change need more water storage capacity for surface water; • Long-term storage of water via groundwater and glaciers are at risk with climate change. • In certain areas increased flooding may lead to more harvest losses.	Expansion of area for food production is generating more GHG/kg product and will cost more water /kg product than intensification on already cultivated land	More competition for water will also be at the expense of natural ecosystems like wetlands.	• Improvement in rain-fed agriculture, reducing land degradation and rehabilitation of degraded land can reduce pressure on (blue[17]) water and land. • Efficient irrigation systems, water storage measures (and other techniques)with sufficient storing capacity • Drought-tolerant crops, salinity-resistant crops • Improved nutrient status of the soil. • Reduce unproductive evaporation from the soil (e.g. mulching) • Water use management, drainage • Integrated stress management • Many other climate-smart agricultural techniques • Reforms to agricultural water rights and price incentives • Agricultural research and development • Reduction of losses of crops and in the food chain (especially in developing countries): less water needed for production • Shifts in consumer behaviour, e.g. from red meat to poultry generally increases water productivity in the food sector. • "virtual water trade"
(10) Agriculture is the largest driver of deforestation, which threatens water security	More extreme rainfall events (droughts and or excessive rainfall) are expected threatening food production	• Deforestation leads to substantial CO_2 emission.	• Deforestation is a direct threat to biodiversity. • Deforested landscapes generally are less resilient to extremes, like extreme weather events.	• Land and water use planning • Forest governance, management and protection of forests • Measures in agricultural sector so that it produces more with less land and water. • Agricultural research and development • Switching from use of freshwater to wastewater • Increasing water use efficiency • Modernising agriculture operations through application of improved practices.

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[17] Blue water: water in rivers, lakes or aquifers that is available for irrigation, municipal and industrial uses; Green water: water in the soil that comes directly from rainfall.

(11) Intensive use of pesticides and fertilisers to improve agricultural yields impact water quality through run-off (result: grey water from nitrate pollution)	Warmer, polluted water	• For production of fertilisers much energy is needed, which results in more CO_2 emission.	Polluted water is a threat to natural water ecosystems: rivers, but also coastal and marine systems.	• Enforcing mechanism for compliance with rules • Agricultural research and development
Trade-offs	**Additional impact of Climate change on the trade-off**	**Possible impact of the trade-off on climate change**	**Possible impact of trade-off on ecosystems, or relation with natural ecosystems**	**Synergies or measures to decrease the mentioned trade-off**
(12) Biofuels: land, water, nutrients for biofuels at the expense of food crops	More CO2 increases crop growth; higher temperature increases crop growth in some (Netherlands, Mongolia, ..) and decreases crop growth in other countries (mainly Africa);	•	If poor farmers are deprived of their land because the land is used for biofuel production, they may over-exploit natural areas in order to get their food (wild animals, herbs, fruit from the forest).	• Investing in agricultural waste as a source of biofuels (second generation biofuels) • Biofuels on marginal agricultural lands? • Certification of biofuels on sustainable production • Lower the expectation (e.g. in EU) of biofuels as a solution for making energy production sustainable • Nitrogen-fixing leguminous trees like Gliricidia sepium can at the same time be used to add nitrogen and organic matter to the soil and can dramatically increase crop yields. At the same time, by pollarding the trees regularly, leaves can be used as fodder while the branches are used as feedstock for electrical power generation. • 'Solar sharing': Production (in Japan) of crops and solar energy simultaneously. Rows of PV panels mopunted above ground and arranged at certain intervalsto allow enough sunlight for photosynthesis and space for agricultural machuinery to be used. • Using waste or marginal land for biofuels
(13) Use of dung for cooking (traditional) and not for fertilisation of agricultural lands	Climate change makes some areas unsuitable for livestock --> no dung available	Burning dung and fuel wood release GHG and is bad for human health.		• Improved stoves • Sustainable production of fuelwood • Solar cooking • Solar energy production • Use dung for biogas production and the remaining slurry for fertilisation of land.

		In most African countries burning dung/fuel wood is major contributor to GHG emissions--> to be avoided		
(14) Hydro-power reservoirs may occupy land that is needed for food production.				• Provide sustainable alternatives for affected communities

Energy and food security (energy for food production)

Trade-offs	**Additional impact of Climate change on the trade-off**	**Possible impact of the trade-off on climate change**	**Possible impact of trade-off on ecosystems, or relation with natural ecosystems**	**Synergies or measures to decrease the mentioned trade-off**
(15) Mechanisation and other modernisation measures helped to increase yields and make agricultural labour more bearable. But energy inputs have increased significantly.	Droughts may reduce window for planting hence more tractors needed at the same time	Changing from oxen traction to mechanisation may have a net benefit for greenhouse gas emissions	Mechanisation allows for more area to be cultivated per household--> conversion of natural areas in crop fields is likely to occur	• More efficient energy use (cutting fertiliser overuse, more precise application of fertiliser, nitrogen fixing, compost etc.) • More renewables • Improved access to sustainable forms of energy • Reconsider subsidies in the agro-sector for fertilisers, electricity, gas. • Integrated multi-use systems (e.g. crop-livestock or agro-forestry) •
(15) Energy is required for the entire food system: food production, harvesting, transport, processing, packaging, and marketing. The full food production and supply chain is	Climate change may increase distance between food production and food consumption areas (e.g. food needs to be imported in areas that lost productive power due to droughts or floods) leading to more energy	idem	Traditional use of fuelwood for artisanal processing of food (e.g. tempeh and tofu production in Indonesia) may lead to overexploitation of forests and land degradation.	• Systems to measure ecological footprint of products and to communicate the results • Reduce post-harvest losses and losses in the value chain and at consumer's level. • Milk cooling devices using solar energy are available. • Biogas can be used to process food (e.g. tofu and tempeh production in Indonesia)

responsible for around 30% of total global energy demand.	demands and larger amounts of GHG emissions related to transport and or the need to process food for storage or less food security			
(16) Developed countries use about 35 gigajoules per person per year for food and agriculture (nearly half in processing and distribution). Developing countries use only 8 gigajoules per person per year (nearly half for cooking). For proper development of the agricultural sector in developing countries, more energy is needed at the right place, especially for fertilisers, processing, storage and transport		Intensification of agriculture requires more energy (inputs) but will still lead to lower GHG emissions/kg food		• Agricultural planning and energy planning should be coordinated.
(17) In several energy programs (traditional) fuelwood for cooking is being replaced by modern energy sources.		If the modern energy source is fossil , then the nett CO2 emission may increase, leading to more greenhouse effect.	Stress on natural resources (trees and shrubs) will diminish if fuelwood is replaced by other energy sources. This is positive and there is also an opportunity and a need to use the shrubs and trees in an alternative way.	• Planning of the use of natural resources and of land use

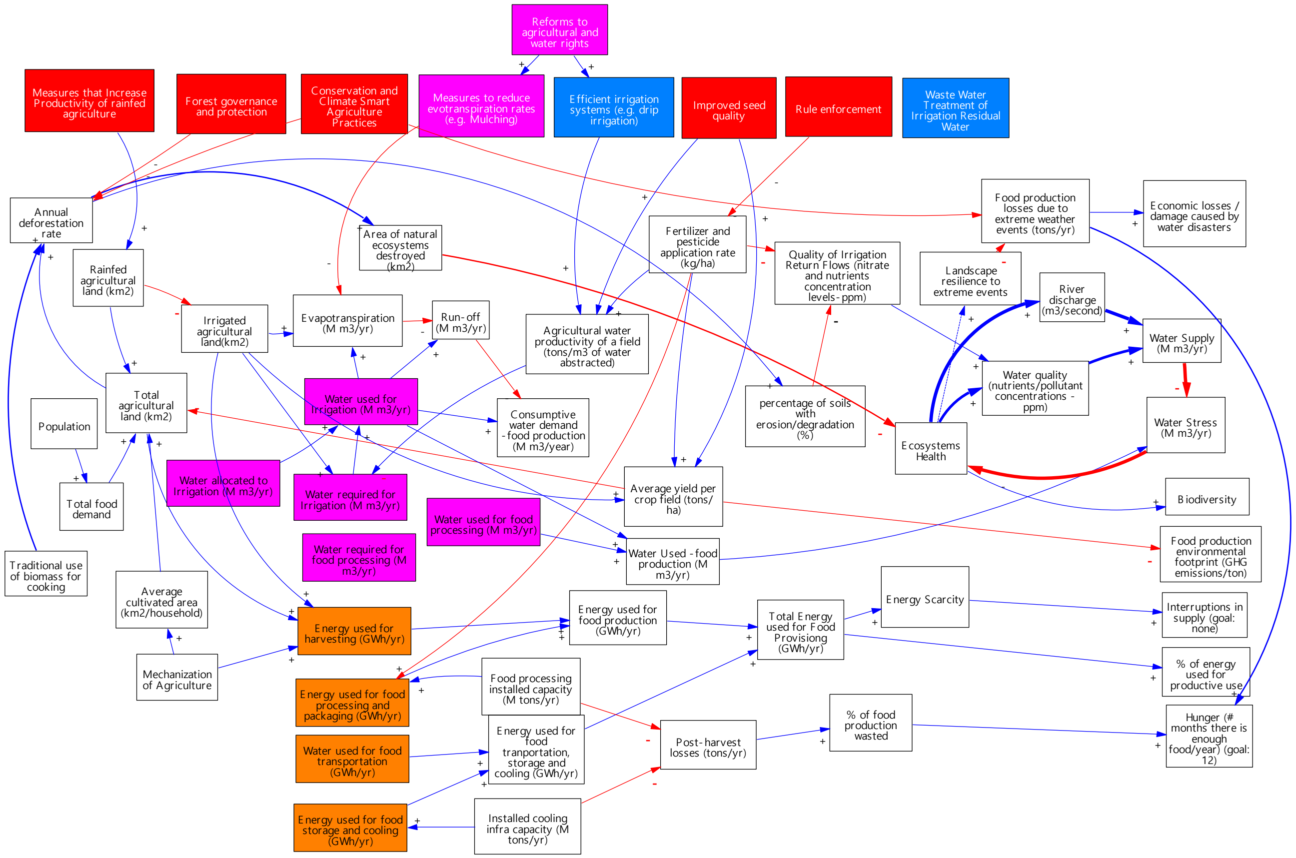
Water, energy & food security

Trade-offs	**Additional impact of Climate change on the trade-off**	**Possible impact of the trade-off on climate change**	**Possible impact of trade-off on ecosystems, or relation with natural ecosystems**	**Synergies or measures to decrease the mentioned trade-off**

Intensification of agriculture	dd	Intensification of agriculture requires more energy (inputs) but will still lead to lower GHG emissions/kg food and lower water use/kg food produced	• Good landscape planning will help to conserve biodiversity and secure long-term provision of environmental services by (semi-) natural ecosystems. • Natural wetlands can serve as water storage facilities so they are important water management tools. • Giving more space to river systems in order to cope better with extreme situations, is also a measure that can be beneficial for nature.	• Improvements in rain fed agriculture and reducing land degradation and rehabilitating degraded land can significantly reduce pressure on (blue) water and land. • Integrated production of food, feed and biofuels can enable recycling of residues and waste products. (e.g. biogas from agricultural waste, crop residues for feed) • Integrated planning across the nexus, involving also city and spatial planning, environmental protection and forestry.
General	The average water supply-demand imbalance is expected to become critical in much of eastern, southern, central and western Asia, in much of Africa and the Middle east, in Southern Europe, the American Southwest, Mexico, the Andean region, and north-eastern Brazil by 2020/2030.	Intensification of agriculture requires more energy (inputs) but will still lead to lower GHG emissions/kg food and lower water use/kg food produced		• Employment outside agriculture to generate money to increase access to food • Food aid • Drought relief measures like control of migration and internal and external conflict. • Strategies that apply physical, policy, and financial tools.

Appendix D: Causal Loop Diagrams of Key Trade-offs and Synergies

CLD 1: Food and Water Security (Trade-offs 10, 12, 15, and 16)



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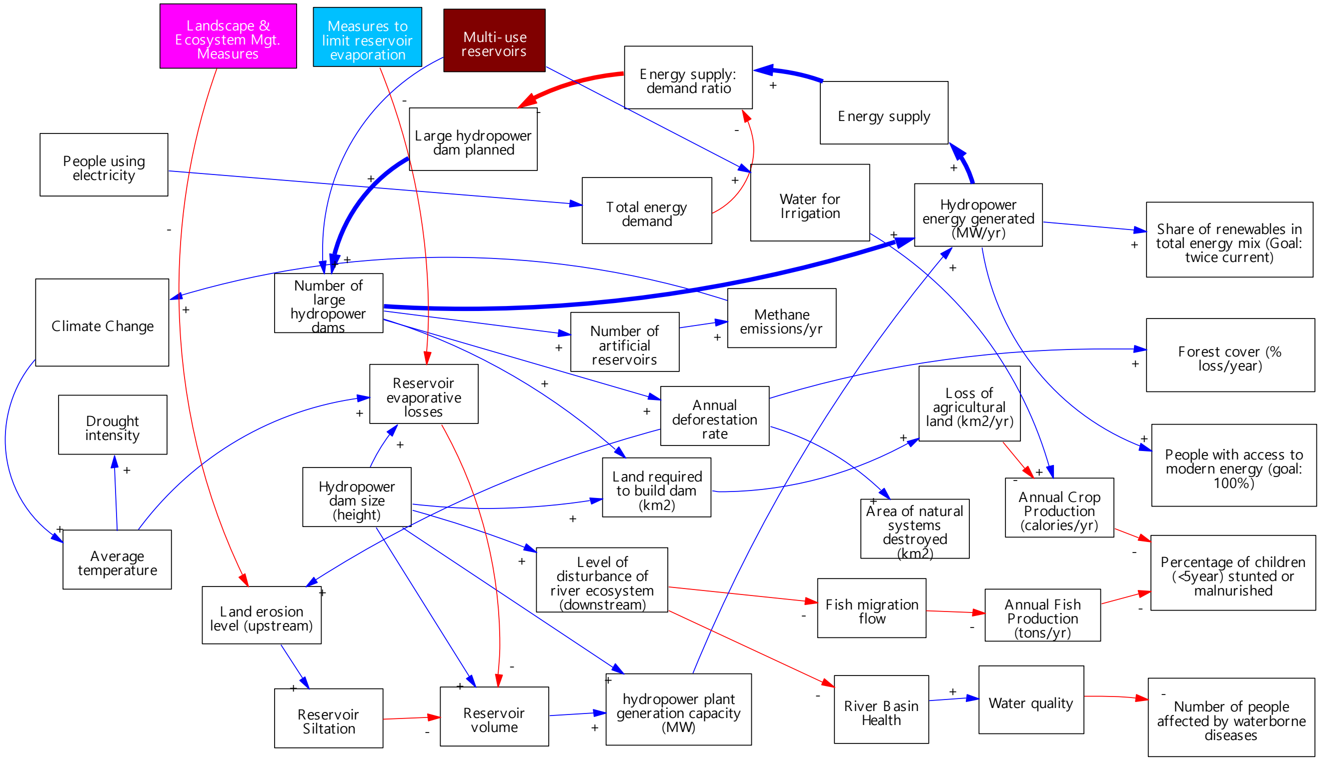
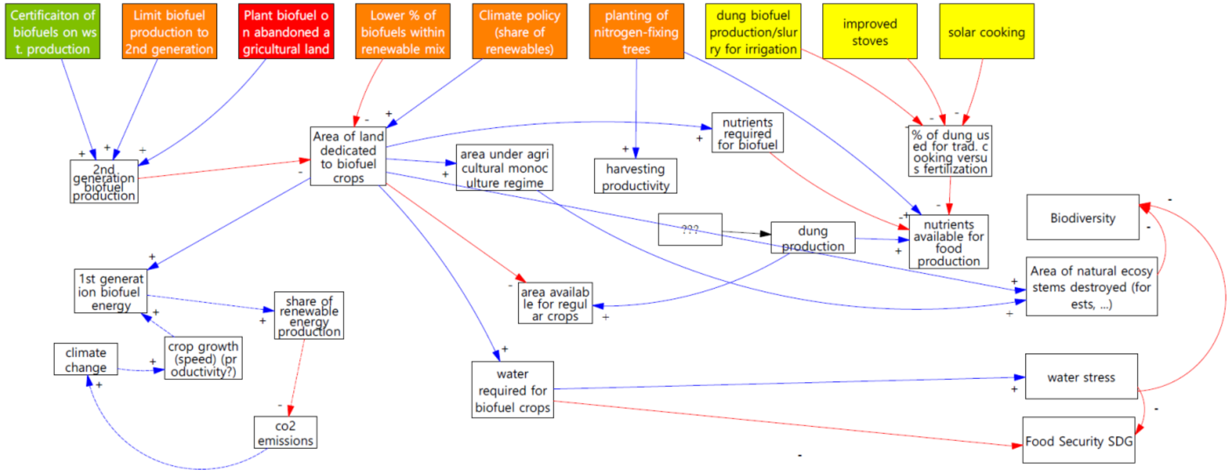
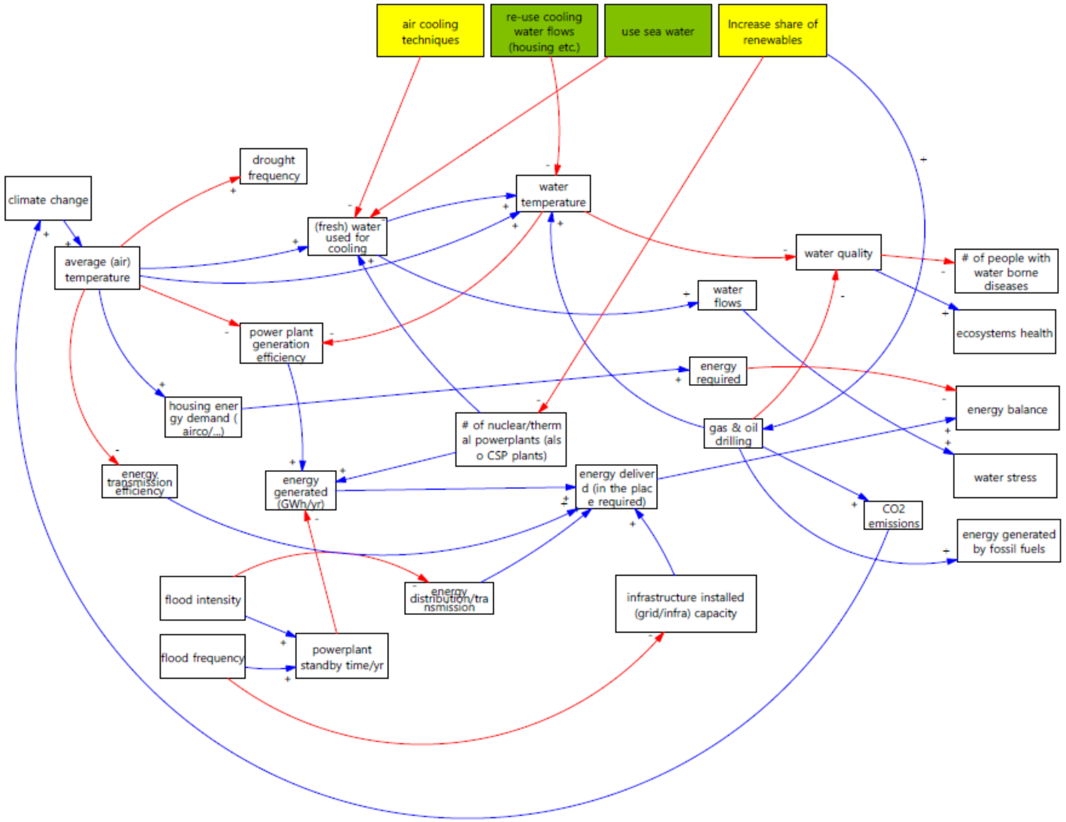
CLD 2: The impact of an increasing share of renewables on water and food security: the impact of large dams (Trade-offs 1 and 14, Water for Energy)



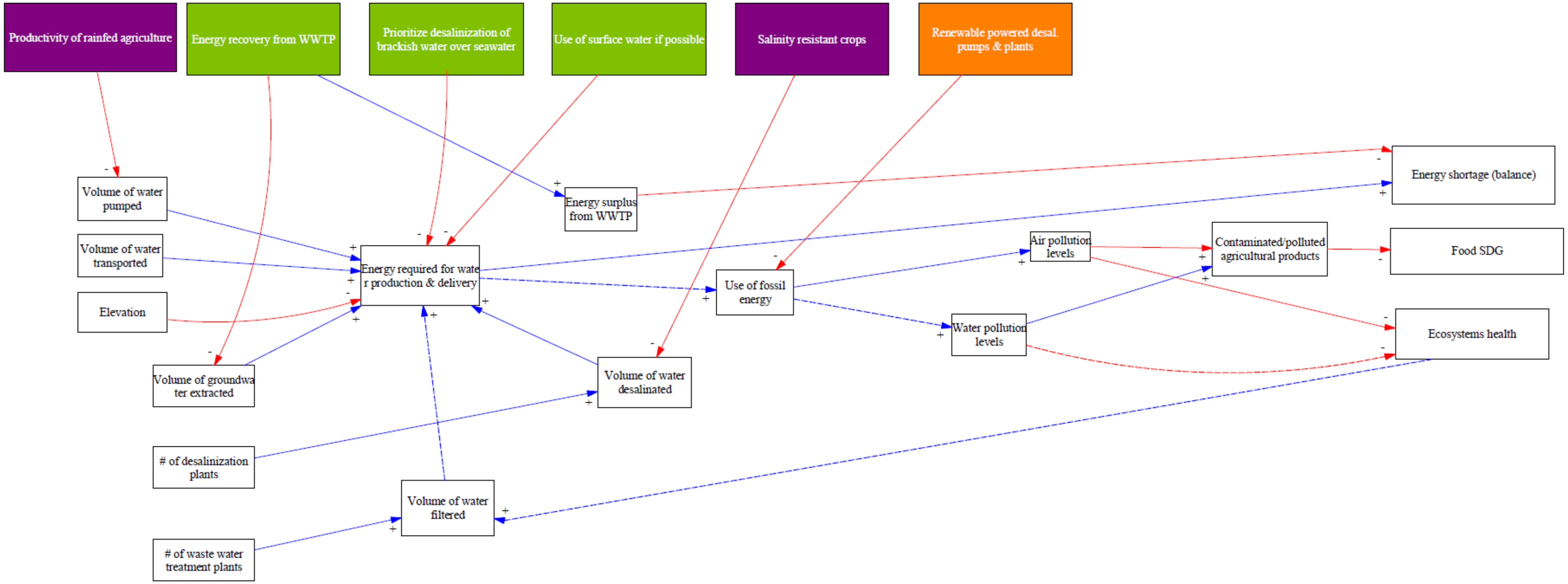
CLD 3: The impact of an increasing share of renewables on water and food security: water and food required for biomass energy production (Trade-offs 4 and 12)



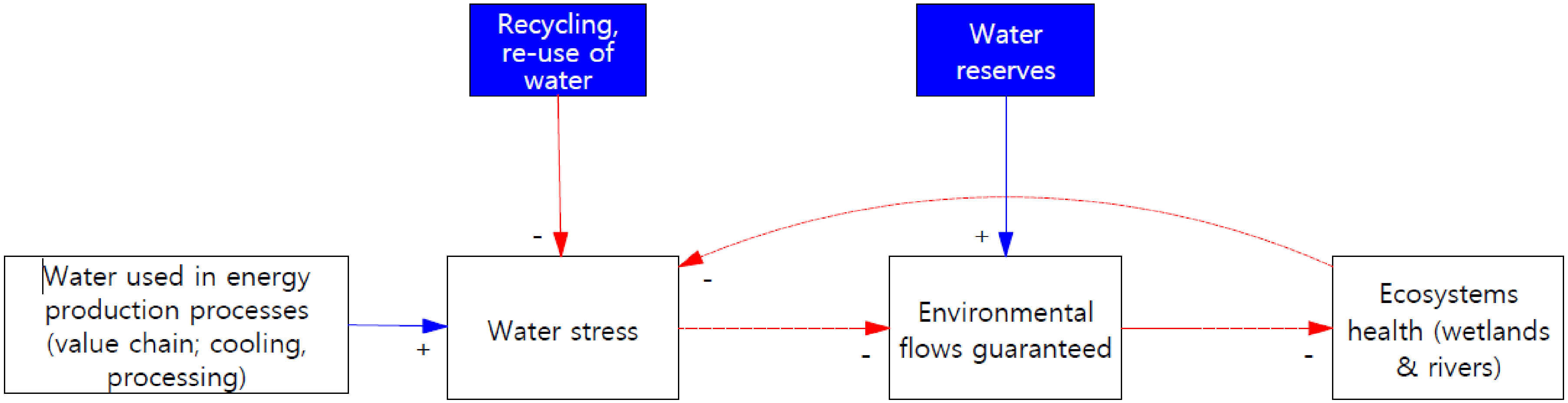
CLD 4: Water for Energy (Trade-offs 2, 3, and 4)



CLD 5: Energy for Water (Trade-offs 7, 8, and 9)



CLD 6: Water for Energy Production Processes (Trade-off 5)



Appendix E: Identifying leverage points

PLACES TO INTERVENE IN A SYSTEM in increasing order of effectiveness:

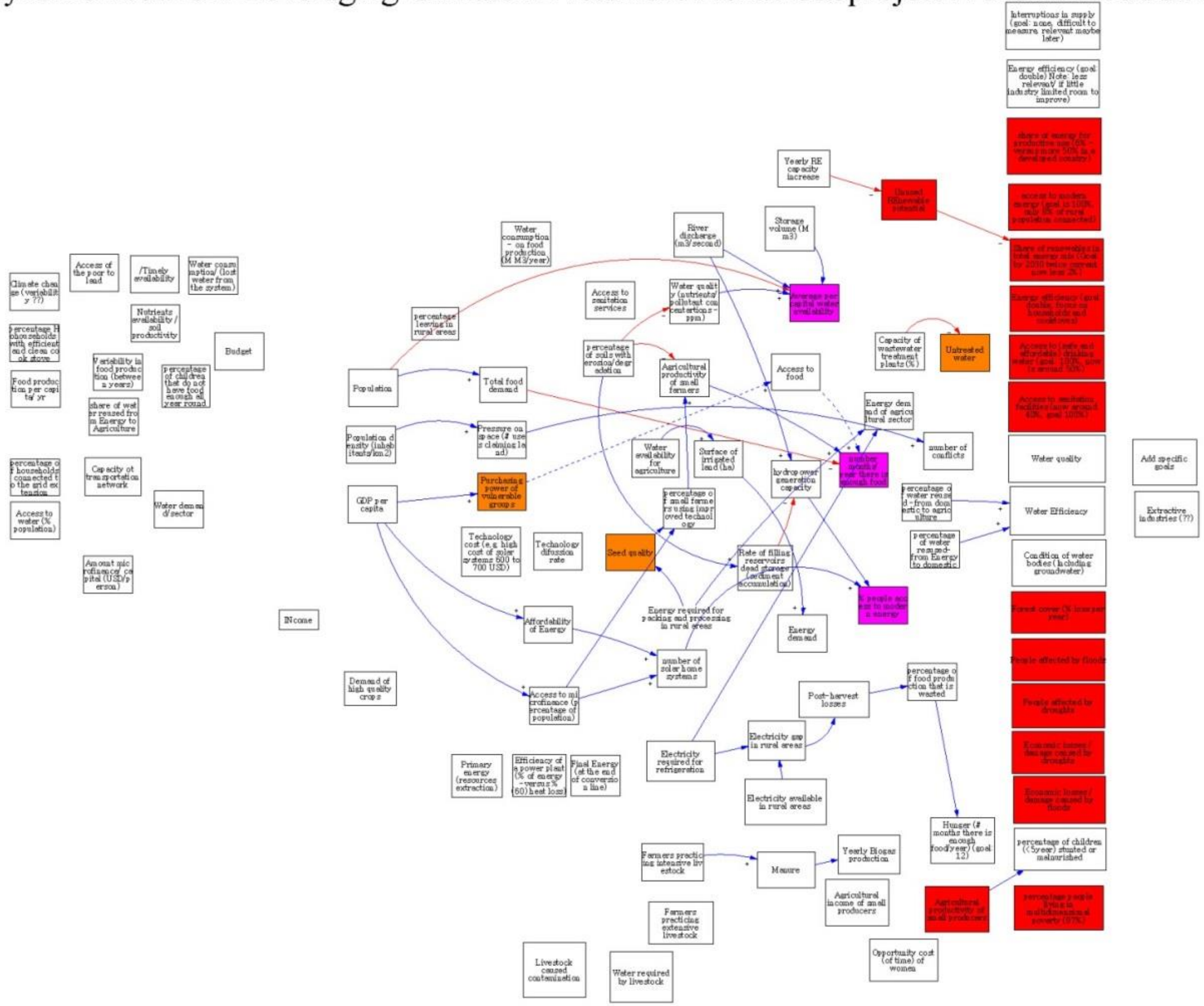
12. Constants, parameters, numbers (such as subsidies, taxes, standards).
11. The sizes of buffers and other stabilizing stocks, relative to their flows.
10. The structure of material stocks and flows (such as transport networks, population age structures).
9. The lengths of delays, relative to the rate of system change.
8. The strength of negative feedback loops, relative to the impacts they are trying to correct against.
7. The gain around driving positive feedback loops.
6. The structure of information flows (who does and does not have access to information).
5. The rules of the system (such as incentives, punishments, constraints).
4. The power to add, change, evolve, or self-organize system structure.
3. The goals of the system.
2. The mindset or paradigm out of which the system — its goals, structure, rules, delays, parameters — arises.
1. The power to transcend paradigms.

Source: Meadows, D. (1999). Leverage points. *Places to Intervene in a System*.

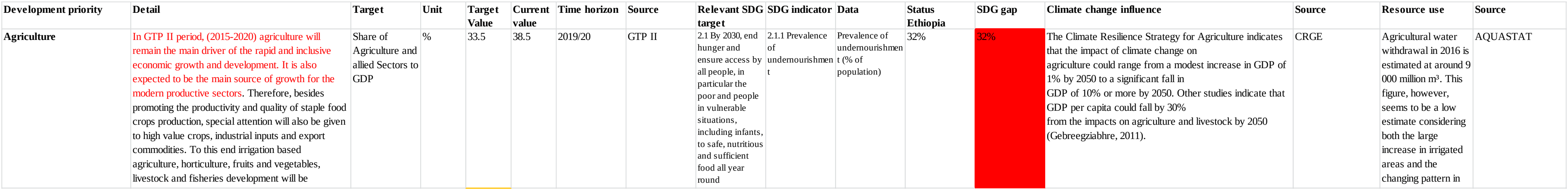
Avaiallable at: http://drbalcom.pbworks.com/w/file/fetch/35173014/Leverage_Points.pdf

Appendix F: Results from the Group Model Building sessions of them Nexus research team Causal Loop

ments\to synchronise\ECN Leveraging Climate INvestment\Nexus Subproject\Vensim Models\Nexus_mod



Appendix G: Nexus development table



Development priority	Detail	Target	Unit	Target Value	Current value	Time horizon	Source	Relevant SDG target	SDG indicator	Data	Status Ethiopia	SDG gap	Climate change influence	Source	Resource use	Source
Agriculture	In GTP II period, (2015-2020) agriculture will remain the main driver of the rapid and inclusive economic growth and development. It is also expected to be the main source of growth for the modern productive sectors. Therefore, besides promoting the productivity and quality of staple food crops production, special attention will also be given to high value crops, industrial inputs and export commodities. To this end irrigation based agriculture, horticulture, fruits and vegetables, livestock and fisheries development will be	Share of Agriculture and allied Sectors to GDP	%	33.5	38.5	2019/20	GTP II	2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round	2.1.1 Prevalence of undernourishment	Prevalence of undernourishment (% of population)	32%	32%	The Climate Resilience Strategy for Agriculture indicates that the impact of climate change on agriculture could range from a modest increase in GDP of 1% by 2050 to a significant fall in GDP of 10% or more by 2050. Other studies indicate that GDP per capita could fall by 30% from the impacts on agriculture and livestock by 2050 (Gebreegziabhre, 2011).	CRGE	Agricultural water withdrawal in 2016 is estimated at around 9 000 million m^3. This figure, however, seems to be a low estimate considering both the large increase in irrigated areas and the changing pattern in	AQUASTAT

See enclosed excel file for complete table.