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Exploring the water-energy-food nexus in Rwanda's Akagara Basin

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Cover photo: Fisherman on the Akagera river tends to his nets © Oliver Johnson / SEI

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1. Introduction

Rwanda has committed itself to becoming a middle-income country by 2020. The country's Vision 2020 and Economic Development and Poverty Reduction Strategies (EDPRS I and II) both set out clear intentions to intensify agriculture, increase national energy output and improve access to modern energy services (Republic of Rwanda 2007; Republic of Rwanda 2013d; Republic of Rwanda 2012). For example, agricultural GDP is expected to grow by 8.5% annually, energy generation is expected to grow from 45MW in 2006 to 563MW in 2018 – mainly through development of hydropower – and electricity access is expected to increase from 17% in 2010 to 100% by 2020. These ambitions are also present at a sub-national level as District Development Plans, which currently include provisions to modernize agriculture, invest in energy production and expand many water-intensive activities, such as mining, industrial development and ecotourism (Republic of Rwanda 2013b; Republic of Rwanda 2013a; Republic of Rwanda 2013c).

These development goals – in tandem with increasing population growth and urbanization – place increasing pressure on limited water and biomass resources, the latter comprising food and fodder, including crop residues and woody biomass widely used for charcoal and firewood. For example, competition over water resources for hydropower, irrigation, and water supply to major towns and various industries has the potential to create serious conflict. Meanwhile, rising demand for charcoal, construction materials and agricultural land is contributing to scarcity of woody biomass. In 2009, 21% of the country's biomass consumption was ascribed to unsustainable use of woody biomass and "the constant flow of charcoal into Kigali, [which] exerts a considerable pressure on the wood resources of the country" (Drigo et al. 2013, p.vii). This demand has stimulated charcoal imports from neighbouring countries, such as Tanzania and the Democratic Republic of the Congo, and the allocation of croplands to woodfuel plantations, such as eucalyptus, which can be seen as more lucrative. In addition, an intensified agricultural sector will demand more energy and water per hectare, although a modernized energy sector less dependent on traditional biomass is likely to be land intensive.

Rwanda has committed itself to becoming a middle-income country by 2020

In order to better tackle these multiple challenges and ensure sustainable development, Rwanda set out its Green Growth and Climate Resilience Strategy (GGCRS) in 2011 (Republic of Rwanda 2011). The GGCRS was developed to guide decisions around natural resource management, investments and policy, as well as to establish demonstration initiatives to support climate resilience activities and community livelihoods, in particular:

- *Land and agricultural transformation:* ensuring sustainable land-use and natural resources management resulting in food security and preservation of biodiversity and ecosystem services
- *Energy transition:* achieving energy security and low carbon energy supply, while avoiding deforestation
- *Societal impacts:* societal protection, including reduced vulnerability to climate change.

This report presents results from research undertaken by the Stockholm Environment Institute (SEI) as part of project led by Albertine Rift Conservation Society (ARCOS) that looked at how the water-energy-food security nexus approach can help promote climate-resilient decisions and model actions in the three selected landscapes along Akagera Basin. The project took place between 2015 and 2018 and was funded by Rwanda's Green Fund (FONERWA) and the Swedish International Development Cooperation Agency (Sida). In this report, we conceptualize natural resource interlinkages through the water-energy-food nexus approach and present SEI's 'nexus toolkit' used in the project. We then present the results of our nexus policy coherence analysis, followed by the results of our quantitative nexus scenario modelling at the national level. We then present the results of our district nexus visioning exercise, before concluding with policy recommendations.

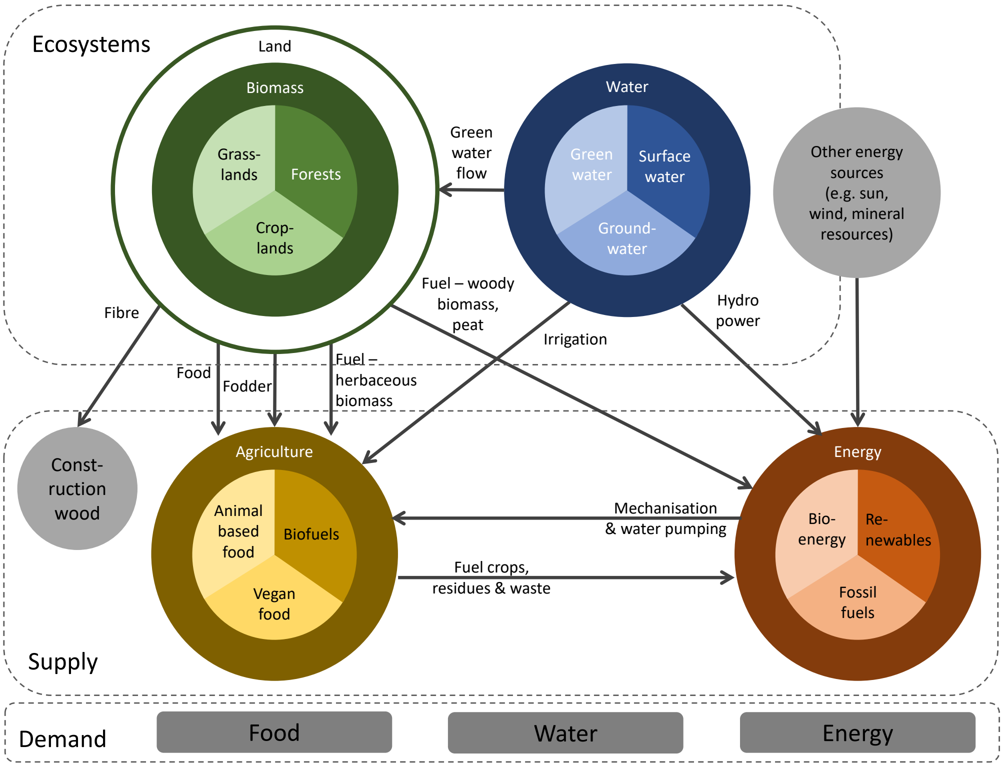
2. Conceptualizing natural resource interlinkages

2.1 Water-energy-food nexus

Agricultural transformation and energy transitions are both underpinned by resource use, and these processes also interact (see Figure 1). In a densely populated country such as Rwanda, transforming agriculture in terms of production practically entails converting subsistence farming systems into high-intensity managed farming systems, since the option of converting non-agricultural land is very limited. Such a transformation depends on higher energy inputs, for instance in the form of fertiliser production, irrigation water pumping, mechanisation, storage and produce transport. Increasing irrigation would enable the farmers to produce more cash-crops, plant and harvest several crops per year, and protect crops against intermittent dry-spells. High intensive farming systems often have negative impacts on surrounding ecosystems, such as fertiliser, herbicide and pesticide leaching into nearby water-bodies, as well as over-use of groundwater and river water (Tilman et al. 2002; Tscharntke et al. 2005; Matson 1997). On the other hand, increasing agricultural production from more intensive farming also results in biomass increase, which for example could be used for pellet production for energy purposes.

Energy transition entails shifting a system that today is based on 80-90% traditional solid biomass fuels burned in inefficient cookstoves to more modern energy services provided by electricity and clean-burning fuels, such as LPG, biogas and biomass pellets burned in gasifier stoves. This is a complex process, and fuel and stove use often continues even when households have access to electricity (van der Kroon et al. 2013). Nevertheless, interventions to increase adoption of cleaner and more efficient fuel use and technologies remains an important part of the process. Agricultural systems could be integral to this process by more efficiently utilising agricultural by-products in the energy system. Halting deforestation is critical in Rwanda. At the same time, affordable options for more sustainable cooking fuels are not readily available. As the economy grows, electricity demand is expected to increase, with hydropower production playing a major role in meeting this demand. However, this may conflict with increased use of water for irrigation, which is a major component underpinning agricultural transformation.

Figure 1. Natural resource flows within agriculture and energy sectors



Note: "Green water" is rainwater which collects as moisture in the soil, Surface water in lakes and rivers and groundwater are known as "blue water".

Pursuit of sustainable development is widely appreciated as a politically negotiated process between different stakeholder groups, each with their own interests and framing of the issue (Giddings et al. 2002; McShane et al. 2011; Leach et al. 2007). As such, efforts to pursue sustainable development in Rwanda raise many critical questions about how to balance different perspectives, options and pathways. For example, would it be best to invest heavily in hydropower to support industry and combat deforestation? Or would hydropower production actually have very little impact on deforestation since the majority of deforestation is caused by the needs of different stakeholder groups (e.g. used for cooking)? Will agriculture be able to meet food demands in 2050, and will there be enough resources to sustainably support this demand? To address these issues, we have used a method which starts by analysing the current policy framework to identify potential conflicts that are further elaborated on using numerical approaching, involving stakeholders throughout the project cycle, as presented below.

2.2 Presenting SEI's Nexus toolkit

The SEI Nexus toolkit contains two complementary analytical approaches to exploring natural resource interlinkages: a policy coherence framework and a set of water-energy-food planning tools.

2.2.1 Policy coherence framework

Understanding conflicts and synergies between the different government policies in Rwanda is key for achieving sustainable development and Vision 2020. We used a framework for analysing policy coherence developed by Nilsson et al. (2012), and a seven-point typology of interactions (framework for interactions assessment) presented by Nilsson et al. (2016) and Griggs et al. (2017) to analyse the policy coherence and characterise interactions between policy objectives (see Figure 2). In this study, we adapted it to assess interactions between agricultural transformations, energy transitions and their impact on natural resources. We adapt this framework to include five possible types of interactions that range from negative (counteracting (-2) and constraining (-1) to positive (enabling (+1), and reinforcing (+2). Neutral interactions are assigned 0 (see Figure 2).

Figure 2: Goal interaction scoring on a five-point scale

Interaction	Name	Explanation	Example
2	Reinforcing	Aids the achievement of another goal	Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
1	Enabling	Creates conditions that further another goal	Providing electricity access in rural homes enables education, because it makes it possible to do homework at night with electric lighting.
0	Consistent	No significant positive or negative interactions	Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.
-1	Constraining	Limits options on another goal	Improved water efficiency can constrain agricultural irrigation. Reducing climate change can constrain the options for energy access.
-2	Counteracting	Clashes with another goal	Boosting consumption for growth can counteract waste reduction and climate mitigation.

Source: Adapted from Nilsson et al. 2016

2.2.2 Scenario modelling tools

The second component of the SEI nexus toolkit comprises a set of water-energy-food planning tools that enable quantitative analysis of natural resource interlinkages under future development pathways. The Water Evaluation and Planning (WEAP) and Long-range Energy Alternatives Planning (LEAP) tools are two of the most common water and energy planning tools used globally today, particularly in data scarce environments.[1] In dialogue with stakeholders, the tool can be applied to test classical "what if" questions

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[1] For more details, see www.weap21.org (WEAP) and www.energycommunity.org (LEAP)

(e.g. what if we increase the energy tariff, subsidize fertilizer, build more irrigation dams, etc.). The stakeholders themselves populate the model with their own data, develop the assumptions, and, jointly with the project team, critique the results of the tool in an iterative way until the model is deemed credible. Moreover, stakeholders analyze the socioeconomic and environmental impacts of the results and compare them with the goals in national strategies and policies. Lastly, stakeholders participate in the formulation of new policies and technical innovations to be tested in the toolkit, thereby supporting the development of new interventions.

In this participatory process the Nexus tool-kit can be used for several purposes:

1. To support the implementation of current policy frameworks such as the EDPRSII and sector specific policy frameworks, to test policy coherence and analyse options for implementation strategies such as various policy mechanisms (e.g. energy and water tariffs, water rights, etc.);
2. To guide new policy development and make policy recommendations, and;
3. To guide investments in new technical innovations.

In this project we have analysed current policies and plans, developed scenario narratives with stakeholders and parameterised the Nexus toolkit. SEI's WEAP and LEAP Nexus Toolkits are modelling tools that use a broad set of data collected in the field and from other sources. The toolkit can then analyse several development pathways, conduct stakeholder analysis of outputs and evaluate different development pathways.

WEAP is an integrated water resource management (IWRM) tool that has been used in numerous river basins around the world. The model works as a scenario planning and decision support system, based on a fully integrated water system simulation model that includes a robust and flexible representation of all water supplies and water demands from all sectors, and allows for the description of operating rules for infrastructure elements such as reservoirs, diversions, environmental flows, canals, etc. The LEAP tool is an integrated modelling tool that has been used in over 190 countries, tracking energy consumption and production in all sectors of an economy. The tool supports a number of different modelling methodologies, including both top-down macroeconomic projections of energy demand, bottom-up engineering-based demand analyses, and hybrid assessments that employ elements of each. Linked together, these tools form the basis of SEI's Nexus toolkit, which provides a dynamic analysis of water, energy and land-use interactions.

Gathering agricultural residues by the Akagera river © OLIVER JOHNSON / SEI

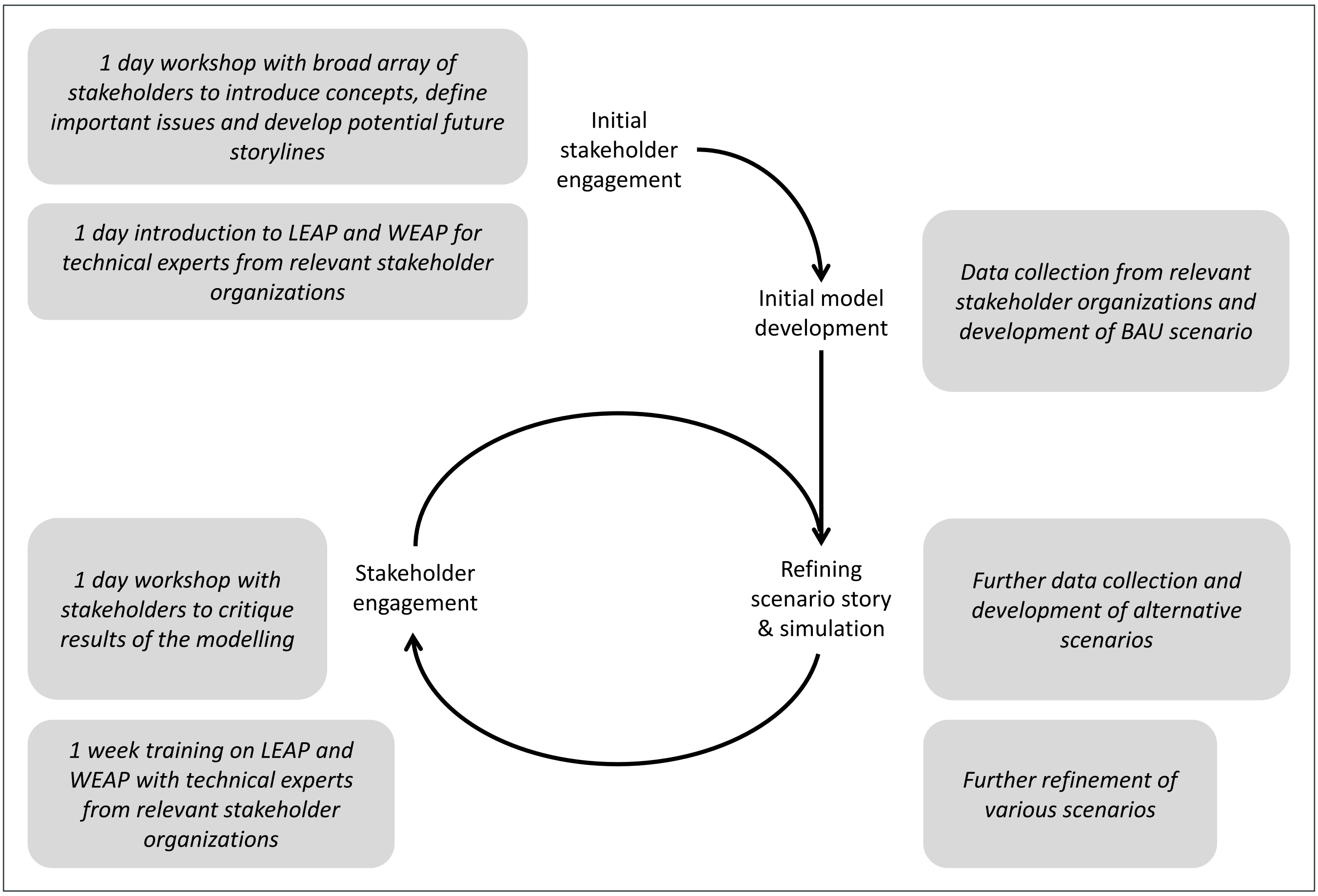
2.3 Stakeholder engagement to operationalise the nexus toolkit

The water-energy-food nexus concept takes an integrated approach to understanding ways in which human development can be pursued without adversely affecting natural resources and ecosystems. However, the complexities of the nexus require careful engagement with stakeholders from across different sectors to better understand key issues and manage conflict and tensions around potential winners and losers of any future change or intervention. Given the potential benefits and pitfalls of participatory processes to understand and seek solutions to the water-energy-food nexus, it is important to design a structured—but flexible—process or method to effectively and sincerely engage with stakeholders in a story and simulation approach (Alcamo 2008), whereby qualitative scenarios—storylines or narratives—describing the broader picture of future development are quantified for use in computer-based modelling tools.

In our research, we sought to co-produce different plausible development scenarios with stakeholders. The Akagera river basin formed the geographical scope of our study in Rwanda. The scenario co-production process in each case study was used to create space for dialogue amongst stakeholders with differing knowledge, experience, priorities and political perspectives on how to address challenges and opportunities pertaining to the nexus. Stakeholders came from the Ministry of Natural Resources, the Rwanda Natural Resources Authority, the Ministry of Agriculture, the Ministry of Local Government, the Ministry of Infrastructure, the Energy Utility Corporation, the Water and Sanitation Corporation and the three districts specifically targeted in the study. Further details of the stakeholder engagement process are given in Section 4.

The process, shown in Figure 3, was based on a set of iterative steps consisting of engagement with technical and non-technical stakeholders to identify the current state of affairs and posit scenarios about how the future might unfold, followed by quantitative modelling of these scenarios. In a workshop setting, stakeholders and the project team jointly developed the assumptions, populated the model with their own data and critiqued the results of the tool in an iterative approach until the model was deemed credible. In addition, stakeholders analysed the socioeconomic and environmental impacts of the results and compared them with national strategy and policy goals. Lastly, stakeholders participated in the formulation of new policies and technical innovations to be tested in the toolkit, thereby supporting the development of new interventions.

Figure 3. Iterative participatory scenario planning



Source: Johnson and Karlberg (2017)

3. Policy coherence around natural resource use in Rwanda

In this section, we assess the coherence of the current policy framework pertaining to the water-energy-food nexus and the interactions between policies to establish where the country is heading (i.e. its development goal) and identify any potential policy inconsistencies. National policies on growth and development and environment, in addition to sectoral policies on agriculture, water, and energy, were analysed to 1) determine the objectives for each sector and 2) assess the interactions between policy objectives, identify any potential policy inconsistencies, and highlight trade-offs and synergies between them. The policy coherence analysis comprised creating an inventory of policy objectives and undertaking an assessment of interactions through a screening exercise.

3.1 Assessing policy objectives and interactions

The first step involved a review of key sectoral policies related to food/agriculture, water, energy, forestry and environment, and national policies on growth and development (see Table 1). For each policy, we analysed the main goals (macro-level objectives) and associated specific objectives with national targets (meso-level and macro-level objectives).

Secondly, to assess and characterise interactions between policy objectives, we used the adapted five-point typology of interactions, set out in Section 2.2.1. The aim was to identify any potential inconsistencies and highlight trade-offs and synergies between water, energy and food/agriculture policies, and between these sectoral policies and national development and environmental policies.

Table 1. Water-Energy-Food Nexus policy framework

Sector	Policy document
National	Vision 2020 revised Economic Development and Poverty Reduction Strategy II (EDPRS II 2013-2018) Green Growth and Climate Resilience Strategy National Strategy for Climate Change and Low Carbon Development (GGCRS) (2011)
Agriculture	Strategic plan for the transformation of Agriculture (Phase III) 2013 National Fertilizer Policy (2014)
Energy	Rwanda Energy Policy 2015 Energy Sector Strategic Plan (2013-2018) Rural Electrification Strategy (2016) Rwanda Supply Master Plan for Fuelwood and Charcoal (2013)
Water	Water and Sanitation Sector strategic plan 2013-2018 Rwanda national policy for water resources management (2011) National Water Supply Policy (2016) Irrigation Master Plan 2010
Forestry	National Forestry Policy
Environment	Five Year Strategic Plan for the Environment And Natural Resources Sector - 2014 – 2018 National Environment Policy

To map interactions, we used a screening matrix which presents sectoral, development and environmental policy objectives on the horizontal axis and the same sectoral, development and environmental policy objectives on the vertical axis. In this study, we assessed and ranked interactions at the level of meso/macro level objectives, consolidating 27 policy objectives (4 development policy objectives; 5 water policy objectives; 6 policy objectives; 7 food/agriculture policy objectives and 5 environmental objectives) into 9. For each policy objective on the horizontal axis, its interaction with other policy objectives on the vertical axis was assessed and a score was assigned to the interaction, using the five-point scale detailed in Section 2.2 and shown in Figure 2.

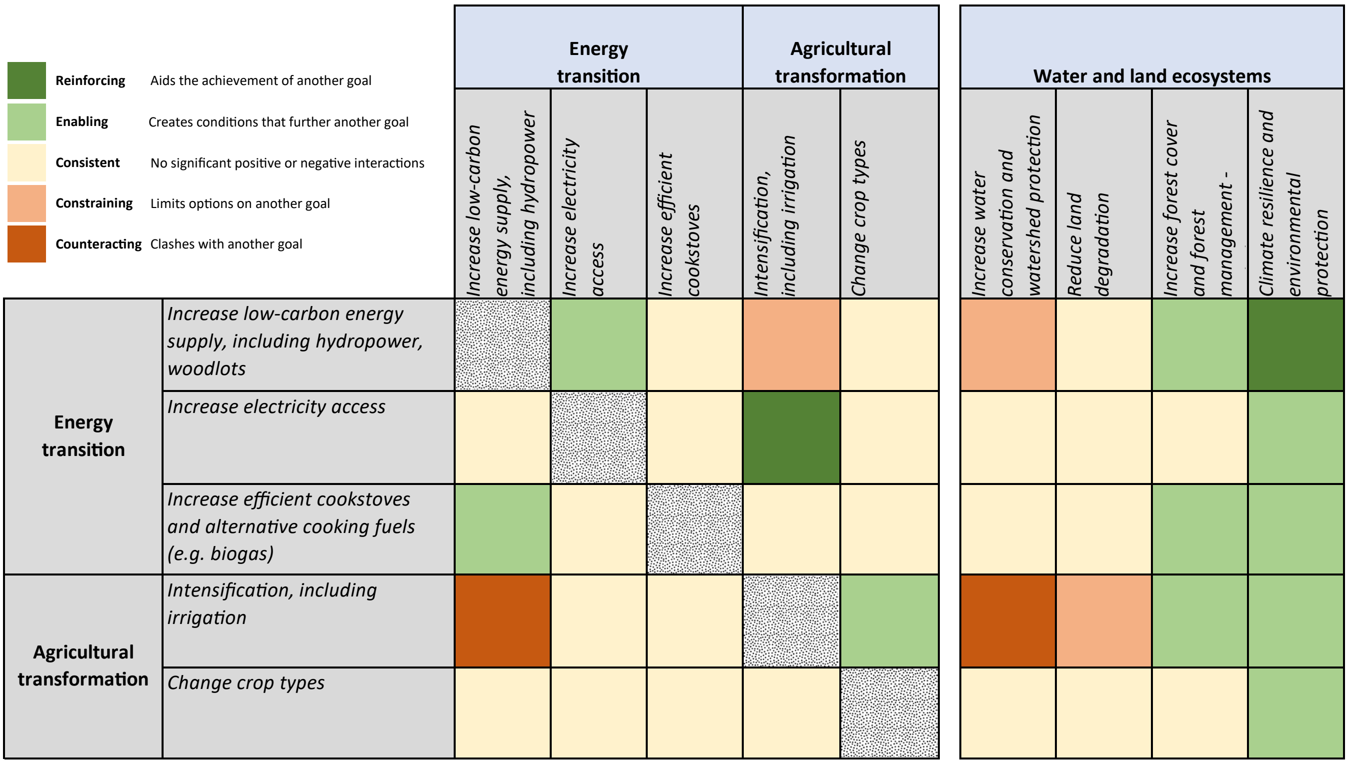
3.2 Mapping policy coherence

From our mapping shown in Figure 4, several policy objectives seem to be both positively and negatively impacting each other. Energy transitions could constrain agricultural transformations if water were to be prioritised for hydropower production rather than irrigation, although there are potential synergies to be found through use of multi-purpose dams. At the same time, the agricultural transformation process is likely to be reinforced by increased energy access. Similarly, agricultural transformation could counteract hydropower generation if irrigation water is allocated to upstream fields and consumed. On the other hand, higher agricultural production leads to more agricultural residues that could be used for biogas or pellet production, for example.

Higher water abstraction for hydropower and irrigation may conflict with the goal of increasing water conservation and watershed protection. Agricultural intensification may also lead to land degradation. On the other hand, a transformation of both the energy and agricultural sectors may reduce the pressure on forest cover; hence these goals could potentially be enabling. Lastly, the transformation processes could also impact positively on reducing climate impacts and mitigating climate change, particularly if low-carbon energy systems are established and land management practices that promote resilience are pursued.

In order to assess if these interactions are important to account for in the planning processes, a quantitative assessment is needed, particularly to understand the impacts certain interactions will have in different situations (or scenarios). We present such a quantitative assessment in the next section.

Figure 4. Policy coherence



🟩	**Reinforcing**	Aids the achievement of another goal
🟢	**Enabling**	Creates conditions that further another goal
🟨	**Consistent**	No significant positive or negative interactions
🟧	**Constraining**	Limits options on another goal
🟥	**Counteracting**	Clashes with another goal

		Energy transition			Agricultural transformation		Water and land ecosystems			
		Increase low-carbon energy supply, including hydropower	*Increase electricity access*	*Increase efficient cookstoves*	*Intensification, including irrigation*	*Change crop types*	*Increase water conservation and watershed protection*	*Reduce land degradation*	*Increase forest cover and forest management -*	*Climate resilience and environmental protection*
Energy transition	*Increase low-carbon energy supply, including hydropower, woodlots*	▨	🟢	🟨	🟧	🟨	🟧	🟨	🟢	🟩
	Increase electricity access	🟨	▨	🟨	🟩	🟨	🟨	🟨	🟨	🟢
	Increase efficient cookstoves and alternative cooking fuels (e.g. biogas)	🟢	🟨	▨	🟨	🟨	🟨	🟨	🟢	🟢
Agricultural transformation	*Intensification, including irrigation*	🟥	🟨	🟨	▨	🟢	🟥	🟧	🟢	🟢
	Change crop types	🟨	🟨	🟨	🟨	▨	🟨	🟨	🟨	🟢

4. Quantifying natural resource interlinkages in national development pathways

In this section we describe the process by which we quantified natural resource interlinkages in Rwanda and present the results from our scenario modelling using the nexus toolkit.

4.1 Stakeholder engagement

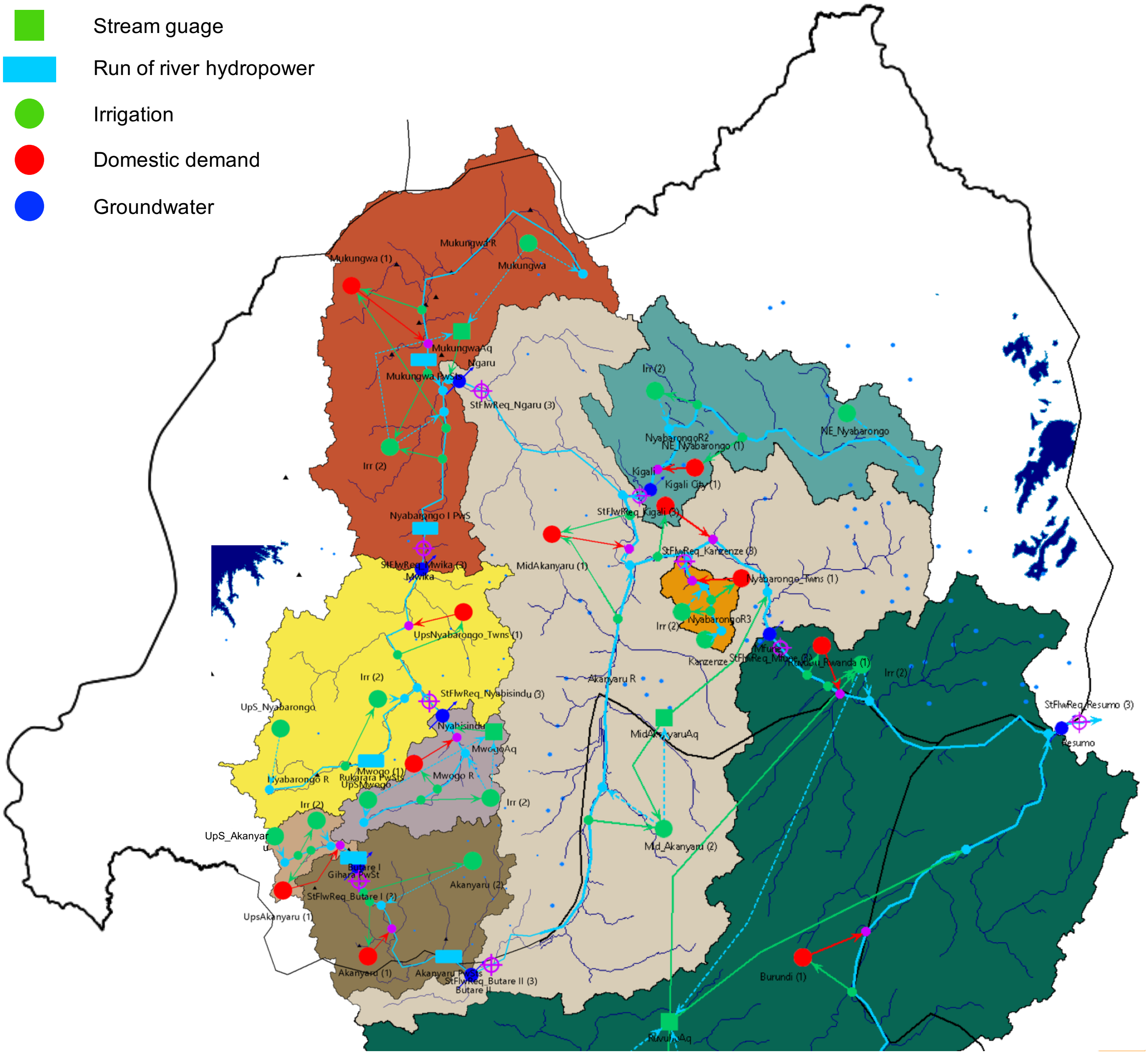
The iterative stakeholder engagement process was implemented in Rwanda through three workshops: an inception workshop in March 2016, a visioning workshop in May 2017 and a validation workshop in January 2018. They all focused on the national level, although visioning workshops were also held within three districts: Bugesera, Kirehe and Rutsiro. Identification of stakeholders and organization of workshops was done in partnership with our local project partner, the Albertine Rift Conservation Society (ARCOS), a conservation NGO headquartered in Kigali. Approximately 25 stakeholders attended the inception, visioning and validation workshops, representing the Ministry of Natural Resources, the Rwanda Natural Resources Authority, the Ministry of Agriculture, the Ministry of Local Government and the three districts specifically targeted in the study. Attracting stakeholders from the government authorities and state-owned utilities in the energy sector was challenging. In the inception workshop, participants were introduced to the water-energy-food nexus concept, mapped out actors and institutions, defined current issues pertaining to the nexus, and created initial scenario narratives. This information was used to develop the initial reference scenario whereby all existing resource management practices were assumed to remain the same, or change according to historical trends, but distributed amongst a growing population as per expected growth patterns. The stakeholders were then asked to generate a second scenario based on weak implementation of the national policy framework. For example, population growth was expected to continue at 2.5% per year. Meanwhile, agricultural transformation would continue to unfold slowly and energy transition would remain hampered by continued dependence on traditional or marginally more efficient biomass energy. During the visioning workshop with the broader stakeholder group, the SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis approach was used. The SWOT analyses were complemented with questions about potential winners and losers under each scenario. As a response to this, the stakeholders defined a third scenario, hereafter called the 'Nexus' scenario. The interaction between stakeholders and scientists generated a revised set of narratives, as well as a clearer understanding among the scientists on which data to include in the LEAP and WEAP models for the Akagera region. In the validation workshop, discussions centred on seeking solutions that address trade-offs. The participatory scenario modelling work led to identification of clear, yet unresolved, conflicts and trade-offs over national plans for water resource use in agriculture and energy, and over current patterns of biomass resource use, as well as development of a 'nexus' scenario that sought to address these conflicts and trade-offs

In tandem with the three workshops, meetings were held with the local technical team, initially to train them on the tools, and later to engage them in critiquing and refining the data, assumptions and results. Technical team members came from the Energy Utility Corporation, the Ministry of Infrastructure, the Ministry of Natural Resources, the Rwanda Natural Resources Authority, the Water and Sanitation Corporation, and representatives from three districts specifically targeted in the study. Energy experts were easier to access than agricultural experts, which proved difficult. The technical team training and meetings led to the emergence of previously inaccessible and invaluable reports and associated data on energy, water and agriculture.

4.2 Scenario development

Based on the information gathered during the different workshops and technical team meetings, as well as semi-structured interviews, local data-repositories made available by the stakeholders and information found in policy documents and the academic literature, the scenarios were developed using WEAP and LEAP modelling software, first qualitatively and then quantitatively. Data and assumptions can be found in Appendix A, as well as in a technical report by Johnson et al. (2018). A map of the Akagera watershed as modelled in WEAP is shown in Figure 5. The map covers roughly 60% of Rwanda's land area and approximately 72% of its population.

Figure 5. Map of Akagera watershed modelled in WEAP



Drawing on the national plans and stakeholder engagement, we present below two development pathways along which Rwanda might travel up to 2050. The first pathway we developed with stakeholders was a *pessimistic scenario* in which national plans are weakly implemented and development is slower than hoped. The second pathway was an *optimistic scenario* in which national plans are fully implemented, leading to substantial transformation of the agricultural and energy sectors, whilst also ensuring sustainable resource use. We named these development pathways pessimistic and optimistic because we felt they accurately reflected the broad consensus amongst stakeholders around what each would mean for achieving sustainable development in Rwanda. In our analysis, the two development scenarios are compared to a *reference scenario* in which development continues along historical trends. Importantly, we do not see these scenarios as definitive in any way; they are simply representative of possible future development pathways for Rwanda, which then allows us to explore some of the potential trade-offs around energy transition, agricultural transformation and natural resource use that require further dialogue and coordinated action.

4.2.1 Reference scenario

In the reference scenario, Rwanda continues to develop according to historical trends, such as continued annual growth in population and GDP of 2.5% and 7.9% respectively. Climate change impacts resource availability via two climate sub-scenarios related to varying rainfall patterns (wetter and dryer than normal), increased temperature and increased humidity. The reference scenario forms the basis upon which all other scenarios are built.

4.2.2 Pessimistic scenario

In the pessimistic scenario, the country's annual population (2.5%) and GDP (7.9%) growth continues, but its ambitious development plans are weakly implemented. Development is slow, and the agriculture and energy sectors fail to substantially modernize by 2050. In the agricultural sector, traditional farming techniques prevail on 80% of the agricultural lands, and croplands equipped with irrigation infrastructure cover only 20% of the land. In addition, fertiliser levels remain low at 8 kg/ha/yr. Consequently, energy needs for agriculture remain low. Meanwhile, in the energy sector, biomass continues to be the main energy source. Because an increasing population continues to use the same type of cookstoves, the demand for domestic use biomass increases. In general, rural households remain unconnected to the national electricity grid. The increasing demand for land and water for agriculture, as well as for wood fuels, results in a large threat to certain habitats such as forests and marshlands, which in turn aggravates soil degradation. Resource use for food and energy production takes a higher priority over meeting environmental flow requirements of limnic ecosystems, or biomass return flows in terrestrial systems, resulting in gradual degradation and a threat to these ecosystems' long-term sustainability.

4.2.3 Optimistic scenario

In the optimistic scenario, growth in population follows the same trend as in the pessimistic scenario, but the country also achieves its goals of modernizing agriculture and energy, and manages to do so whilst ensuring sustainable use of its resources. The agricultural sector develops quickly and by 2050 40% of the farms are now commercial farms, which are managed more intensively than today with higher fertiliser use, mechanisation and access to irrigation according to the national plans. Agricultural lands also expand by 100 000 ha into marshlands.

In the energy sector, a successful cookstove replacement programme is implemented and forest cover is increased by 30%, combined with higher forest productivity, thereby ensuring a more stable supply of biomass for fuel wood. At the same time, all households are connected to the national electricity grid and many of them shift toward biogas and LPG for cooking. For biogas, we used government targets and assumed sufficient livestock to provide the feedstock. We considered growth in fodder demand for livestock at a similar rate to the human population. The agricultural sector becomes dependent on energy inputs, and because of upstream irrigation, water flow for hydropower generation downstream is affected. Rwanda's goal to ensure environmental protection of watersheds, forests, biodiversity and ecosystem services, as well as soil fertility, means that regulation is required. Minimum environmental flow requirements are imposed on irrigation and hydropower generation to control water consumption and secure the functioning of limnic ecosystems.

4.3 Modelling results

In this section we present the results from the participatory scenario modelling using LEAP and WEAP.

4.3.1 Energy transition results

The energy landscape in Rwanda is expected to change dramatically. As shown in Figure 6, there is a substantial increase in energy demand across all scenarios. In the Reference scenario, energy demand rises within all sectors in response to a growing population and economy. The Pessimistic and Optimistic scenarios show similar rises in demand for the public service, commercial and industrial and transport sectors. However, they also present pictures in which rising energy demand is tempered by limited (Pessimistic) and full (Optimistic) implementation of interventions in the household sector related to electrification and use of more efficient cooking fuels and technologies.

Figure 6. Total energy demand in 2010, and in 2050 for different scenarios

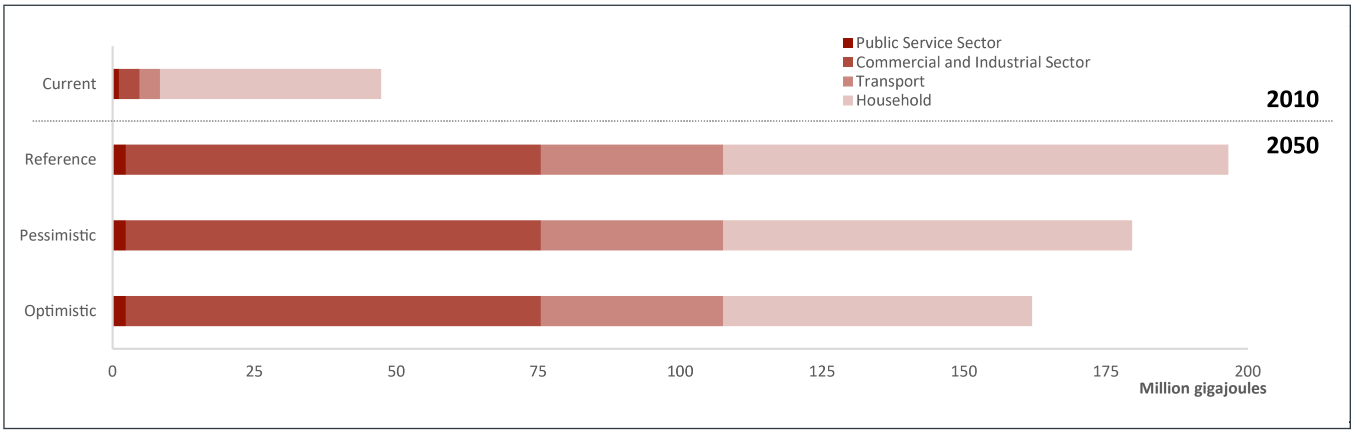


Figure 7 shows the supply and demand balance in the electricity sector across different scenarios up to 2050. For the purpose of showing the balance, supply has a positive value and demand has a negative value. In the Reference scenario, demand is projected to rise ten-fold, from 440 GWh in 2010 to 4 134 GWh, in 2050 (Figure 7). In the Pessimistic and Optimistic scenarios, demand is even higher in 2050: 4,546 GWh and 4,584 GWh, respectively. Although electricity access expanded in both the Optimistic and Pessimistic scenarios at different rates, by 2050 it expanded in both scenarios to 100% of the population, accounting for roughly 400 GWh of additional electricity demand above that of the Reference scenario.

The projection that universal access will lead to only a 10% (400 GWh) increase in demand compared to current levels has both positive and negative aspects. On the positive side, not much more generation is needed to meet this added demand from currently non-connected users. On the negative side, investment is needed in transmission and distribution, and the limited consumption demand from these new users – typically poorer households located in more remote rural areas – makes it difficult to get much return on investment. As such, universal access must be considered a social welfare goal, rather than a profit-driven enterprise.

Figure 8 shows the current domestic electricity mix in 2010 and what it is projected to be in 2050. The LEAP model calculated these projections based on our assumptions of electricity demand growth (linked to population and economic growth, as well as increased electricity access), as well as projected power plant additions based on national infrastructure development plans. The current electricity mix is dominated by diesel (57%) and hydropower (40%), with methane and solar making up 9% and 0.3% respectively. The modelling results show that the electricity mix in 2050 is expected to change considerably, with all scenarios showing peat and methane entering the mix to take a 52% and 9% share respectively, solar increasing to 1.3% and the share of diesel falling to 22%. The share of hydropower reduces in all scenarios, but by slightly different amounts in each, as shown in the bar graph in Figure 8. In the Reference scenario, hydropower will fall to 16%. In the Pessimistic and Optimistic scenarios, it will fall to around 17%, with the least decrease shown in the Pessimistic scenario, where the implementation of fewer irrigation schemes (which are prioritized over hydropower) results in slightly less diversion of water.

As shown in Figure 9, a comparison of household energy demand from cooking across the three different scenarios shows that interventions related to the use of more efficient cooking fuels and technologies can reduce household energy demand by up to almost half. In the Reference scenario, household energy demand rises from 7 778 GJ to 34 920 GJ in response to the growing population; wood and charcoal continue to account for around 95% of this demand, with the remainder coming from small increases in LPG and direct use of agricultural residues. Limited use of more efficient cooking fuels and technologies in the Pessimistic scenario leads to household energy demand in 2050 reaching 27 510 GJ, a 21% reduction compared to the Reference scenario. Wood and charcoal continue to dominate, accounting for 82% of demand, but there is increased use of LPG, agricultural residues

Figure 7. Electricity supply and demand across different scenarios, 2010-2050 (TWh)

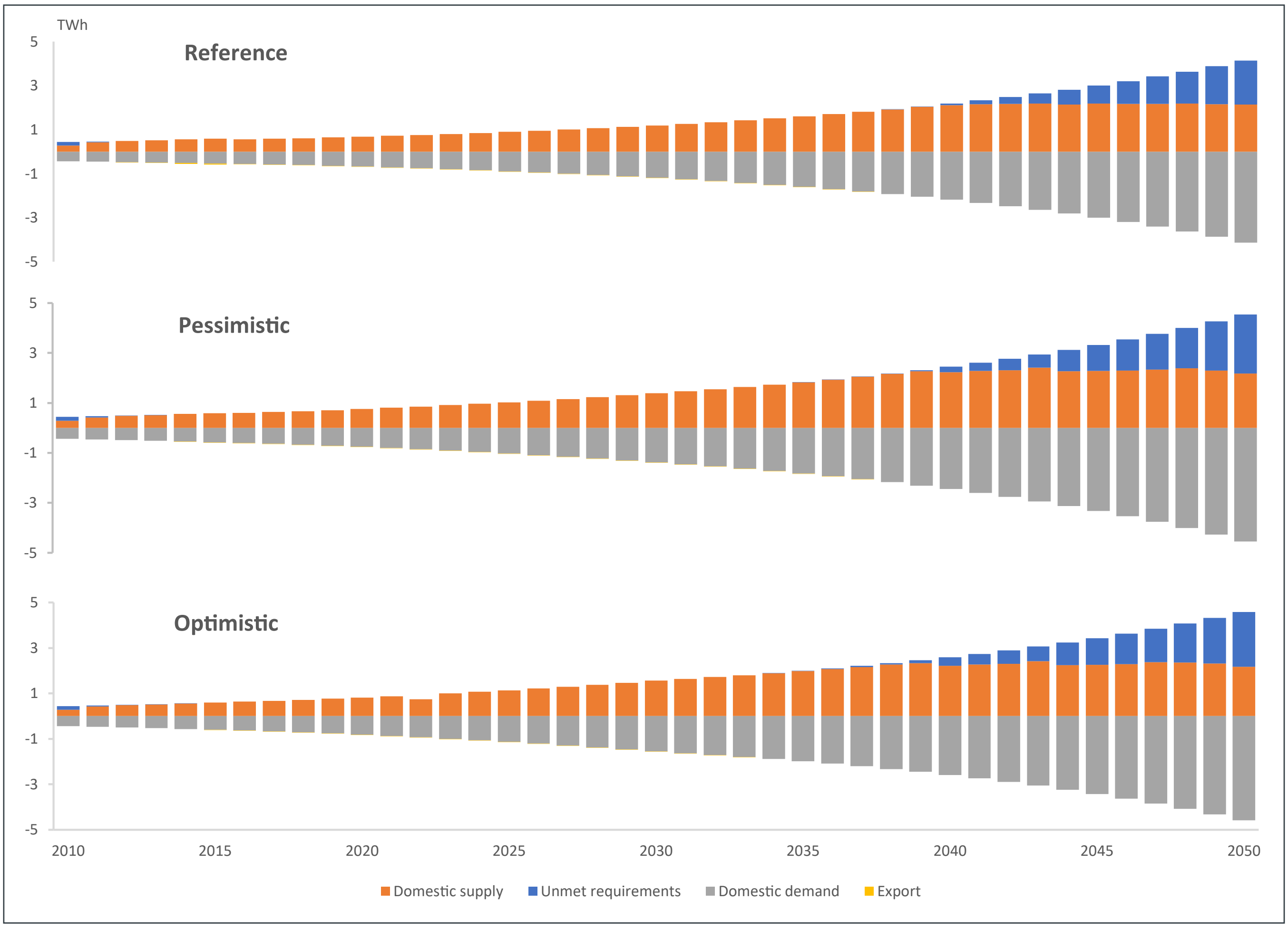
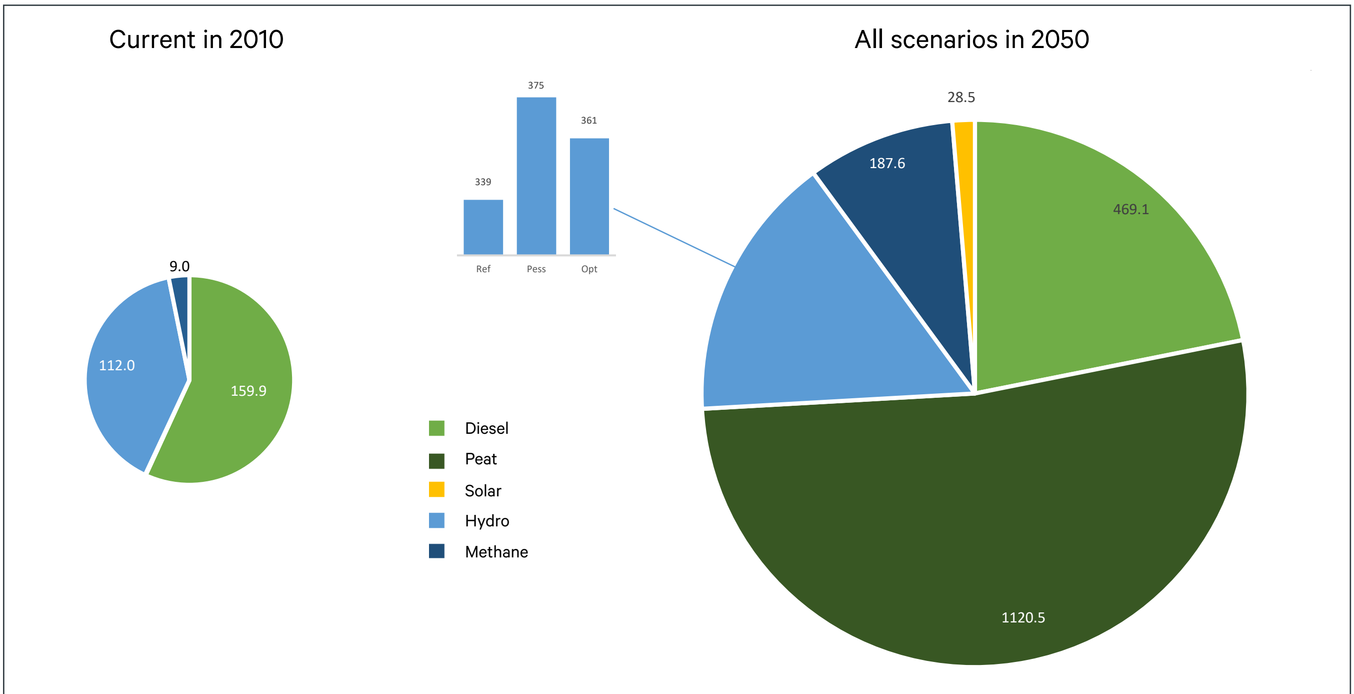


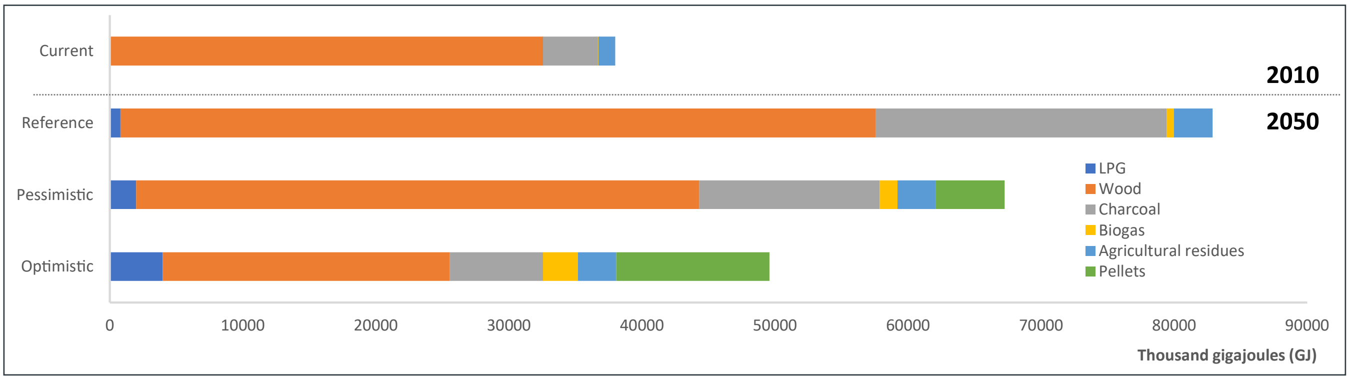
Figure 8. Electricity mix in 2010 and 2050 (in GWh)



Note: Electricity generation in 2050 in all scenarios is the same for all fuels except hydro, which differs according to the bars graphs.

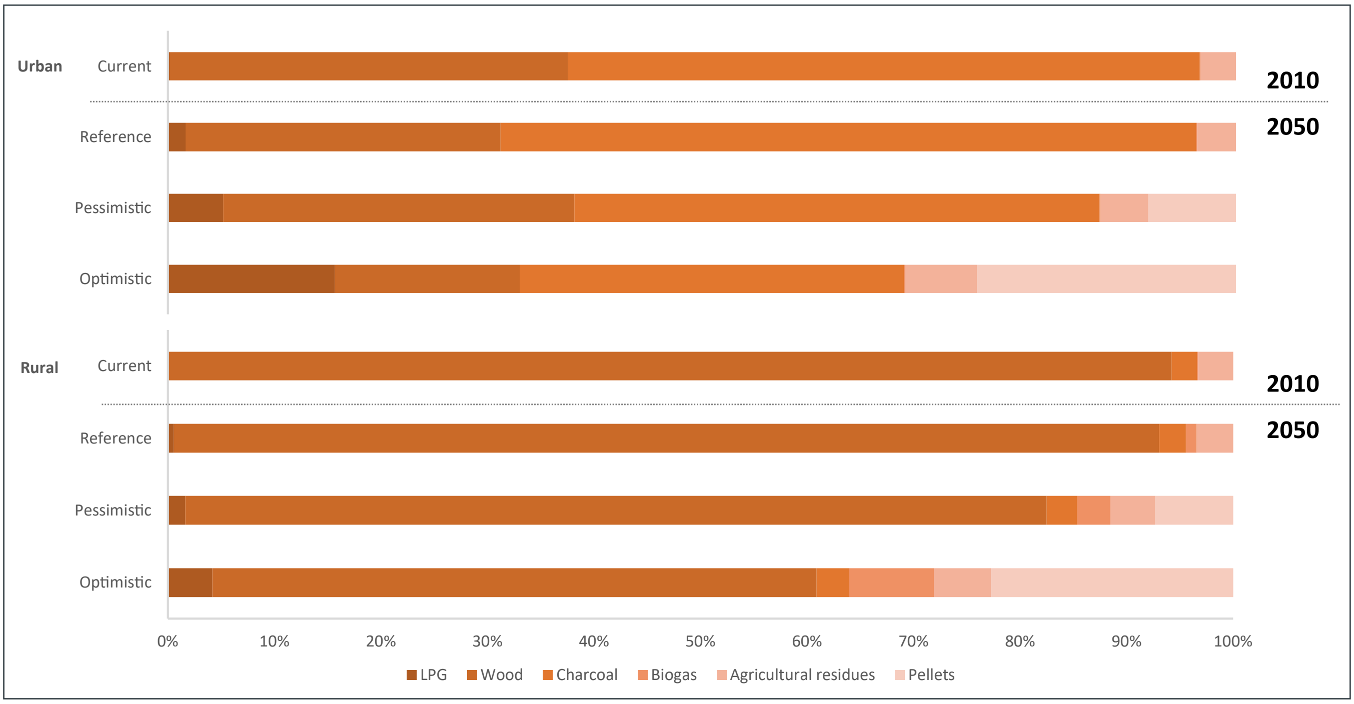
and pellets from these residues. In the Optimistic scenario, we assume effective interventions lead to widespread adoption of more efficient cooking fuels and technologies, leading to a rise in demand to 17 828 GJ in 2050, a 49% reduction in household energy demand for cooking compared to the Reference scenario. Wood and charcoal account for much less of this demand – only 53% - with LPG, agricultural residues and pellets making up 46% of demand, and the remaining 1% coming from biogas.

Figure 9. Different scenarios in household energy demand for cooking fuels in 2010 and 2050



When looking at household energy demand scenarios from the perspective of urban and rural households, we discover differences in demand for cooking fuel also between locations (see Figure 10). In keeping with our understanding of charcoal as a primarily urban fuel, we see that in urban settings it accounts for 65%, 49% and 36% in the Reference, Pessimistic and Optimistic scenarios, respectively. In urban settings, wood is also prevalent, but somewhat reduced in the Pessimistic scenario and greatly reduced in the Optimistic scenario. In rural settings, wood completely dominates in the Reference and Pessimistic scenarios, dropping only slightly from 92% to 80% of demand. In the Optimistic scenario, there is much greater change, with wood reducing to only 38% of demand. In the Optimistic scenario, rural areas experience a considerable rise in the use of biogas and pellets from agricultural residues, whilst in urban areas there is greater rise in the use of LPG and pellets.

Figure 10. Different scenarios in household cooking fuel mix in 2010 and 2050



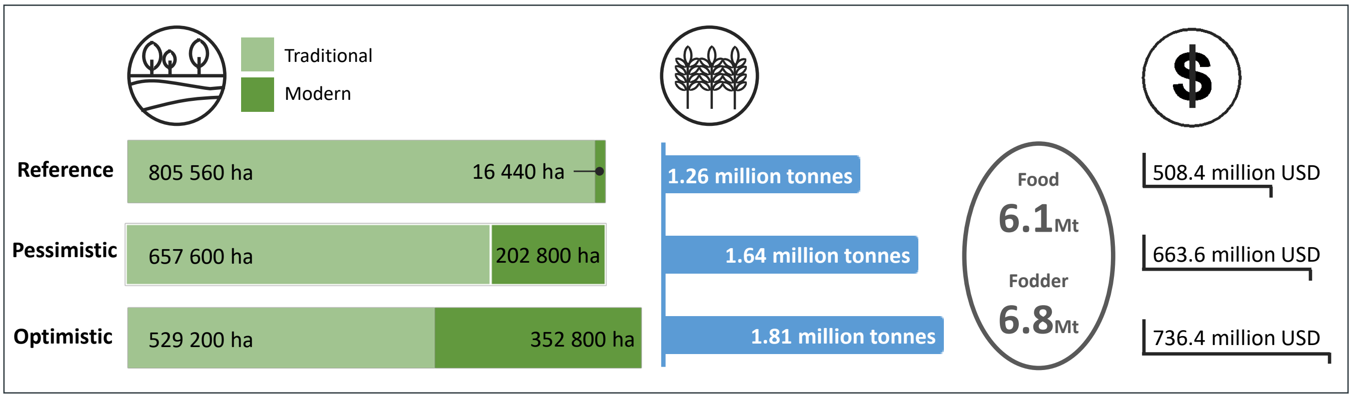
4.3.2 Agricultural transformation results

In WEAP, we modelled a gradual transformation of the agricultural systems toward more modern agriculture in 2050 through shifting of 'traditional' cropland area to more 'modernized' cropland and a small expansion of modernized cropland into wetlands (see Appendix A for further details). As shown in Figure 11, our WEAP modelling results from this transformation showed that this leads to yield increases of approximately 30% and 45%, in the Pessimistic and Optimistic scenarios, respectively. Subsequently, the value of the crop production increases proportionately, as we did not assume any changes in cropping patterns.

At the same time, food demand is expected to increase by approximately 60% by 2050 compared to current numbers, assuming an average balanced diet. A comparison between the supply of grain and grass (vegetarian based food items) to meet food demands and fodder, indicates that the unmet demand for grain and grass will continue to grow in all three scenarios, due to high population growth outpacing production increases. By 2050, the unmet demand for food is expected to more than double, increasing from the current 1.1 Mton/yr, to 2.5, 2.1 and 1.9 Mton/yr, for the Reference, Pessimistic and Optimistic scenarios, respectively. For fodder, the supply-demand gap by 2050 is similar, increasing from 2.0 Mton/yr currently to 3.7, 3.9 and 3.9 Mton/yr for the Reference, Pessimistic and Optimistic scenarios, respectively. Despite higher productivity in the Optimistic scenario, the fodder gap is the same in both Pessimistic and Optimistic due to some of the landscape (i.e. meadows and pastures) being allocated to forest plantations.

It is worth noting that the unmet demand for fodder could easily rectified by utilising crop residues as feed. Annual residue production varies between 12-17.5 Mton/yr, depending on scenario. To what degree farmers today already practice this is unknown. However, these residues also present a great opportunity to meet increasing energy demands, i.e. by producing pellets or biogas. Even without this potential trade-off between use of biomass for animal feed or energy, it may not be economically or logistically feasible to collect and use agricultural waste for these purposes. Moreover, it is important to ensure some biomass is left in the fields to provide ground cover nutrient recycling. Any effort to promote agricultural residues for this type of use must factor in this sustainability need.

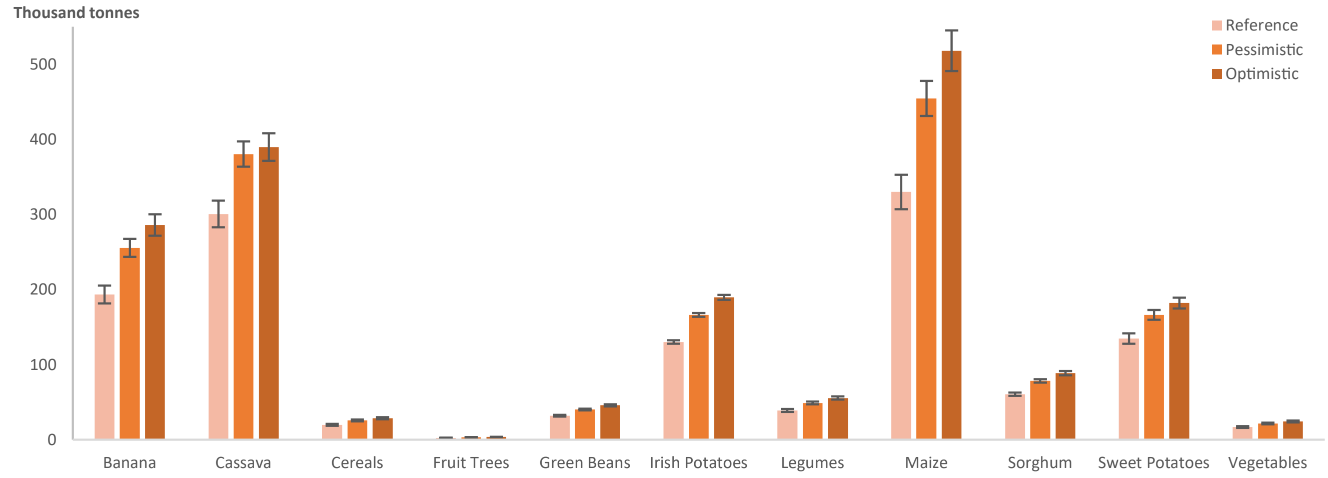
Figure 11. Agricultural transformation in 2050



In the model, total crop production was estimated for the eleven most common crops in the region (Figure 12). The Reference scenario had the lowest production, whilst the Optimistic scenario had the highest. Reference scenario results can be considered credible as they are based on the current situation. However, crop production in the Optimistic scenario appears somewhat low compared to the Reference scenario. Despite a considerable increase and improvement of inputs such as fertiliser and water on 40% of the cropland, production growth amounts to only 45%, or a doubling of yield on the modernised farmland. It is possible that water and nutrient availability impacts are not appropriately captured in the tool. Therefore, the results for the Optimistic scenario should be interpreted with some caution. Moreover, tea and coffee model outputs were excluded from the results as we did not feel confident about their accuracy.

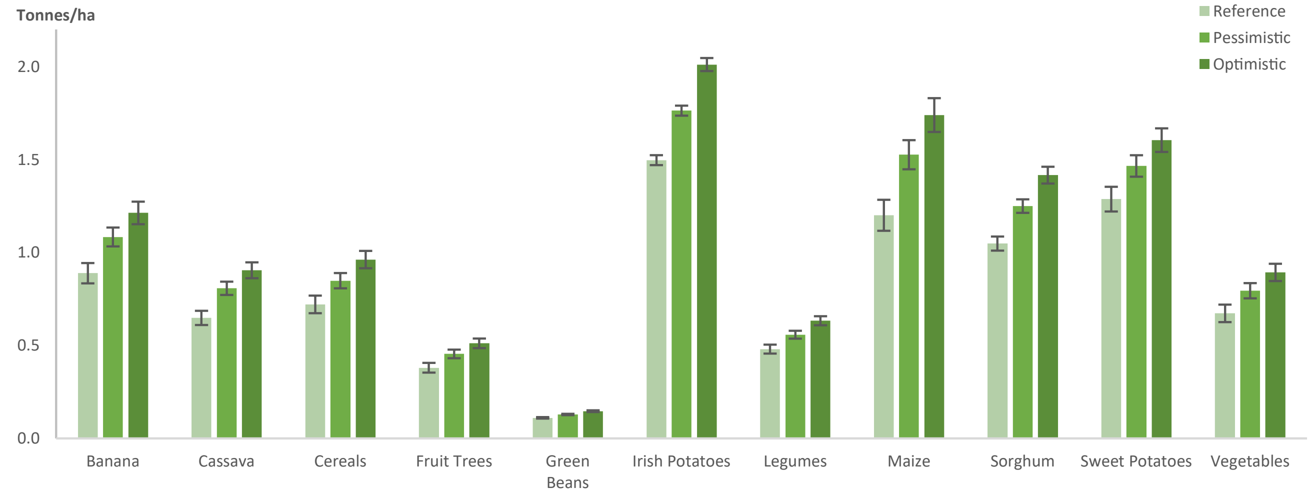
Annual average yields in crop production for 2050 were estimated, and thus follow a similar pattern (see Figure 13). The impact of improved management in the Optimistic scenario was again somewhat small.

Figure 12. Different scenarios in crop production, 2050



Note: Error bars denote the values for dry and wet climate sub-scenarios for each development scenario. Solid bar values represent average production across dry and wet climate sub-scenarios.

Figure 13. Different scenarios in crop yield, 2050



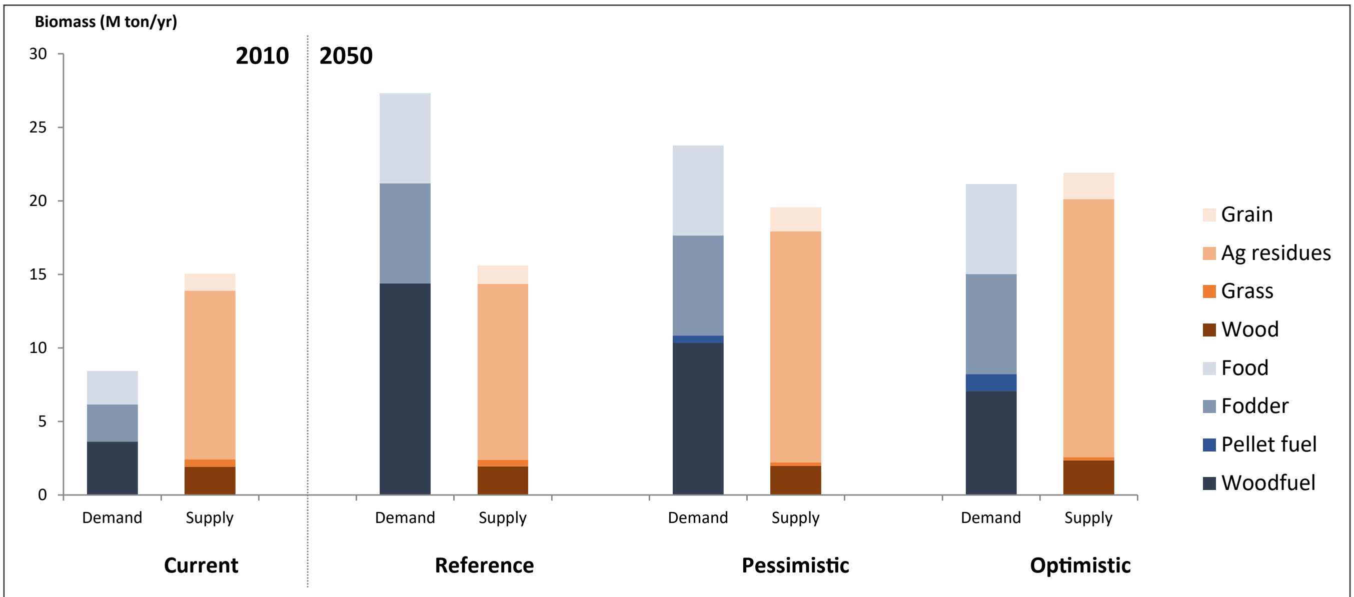
Note: Error bars denote the values for dry and wet climate sub-scenarios for each development scenario. Solid bar represent average values across dry and wet climate sub-scenarios.

4.3.3 Impacts on resource use and sustainability

In our scenarios, the energy and agriculture sectors either remain in status quo (Reference), undergo limited change (Pessimistic) or experience extensive transition and transformation (Optimistic). Given the dependence of both these sectors on natural resources, each pathway has significant implications for resource use sustainability in Rwanda.

In all three scenarios, biomass scarcity continues to be a constraining factor with potential negative consequences for land-based ecosystems (Figure 14). Wood demand continues to exceed supply in all three scenarios. This also results in continued high risk for deforestation and forest degradation in future if forests are not managed properly. In addition, the energy sector is expected to supply more energy from domestic peat resources, which some argue is a cost competitive alternative to the current widespread use of diesel (for example, see Hakizimana et al. 2016). The projection that it will provide over half the country's power by 2050 may seem improbable, but even if the figure is lower, it will still significantly threaten wetland ecosystems, as highlighted by Twagiramungu (2006) and ECODIT LLC (2014). In our estimation of cropland biomass availability, we assumed that 20% of above-ground biomass was returned to the soil to prevent degradation. Yet the supply of crop residue exceeds the demand for fodder by a factor of three to four, which means that it is possible to both meet fodder demands and utilise the remaining residue for energy production, e.g. pellets or biogas. Together with solar energy, this could become an important option for future energy generation in the country.

Figure 14. Different scenarios in biomass supply-demand in 2010 and 2050



Note: Biomass energy demand includes demand from all sectors, not just households

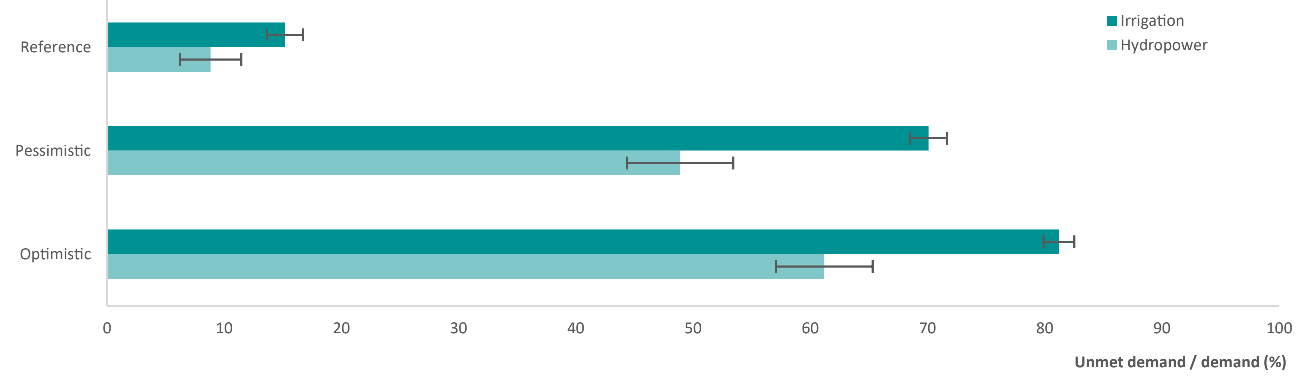
New investments in irrigation and hydropower infrastructure increase the demand for water over time. Our estimations indicate that by 2050, water availability will not meet rising demand in either of the sectors in all three scenarios (Figure 15). On an annual basis, unmet demand for irrigation is higher than total demand by approximately 70% and 80% for the Pessimistic and Optimistic scenario, respectively. The corresponding figures for hydropower are 50 and 60%, respectively.

As a consequence, it appears that we have a paradox of findings: what we coined together with stakeholders to be a "pessimistic" scenario from the perspective of slow development and limited implementation of national plans might not be so pessimistic in terms of sustainable natural resource use. Additional investments in both irrigation and hydropower infrastructure beyond the level of ambition in the Pessimistic scenario shows diminishing returns in both food and energy production, due to limited water availability, as clearly demonstrated for energy (Figure 8) and agriculture (Figure 11).

With such high potential competition around limited water resources, there is a high risk of over abstraction, with concurrent negative impacts on limnic ecosystems and groundwater. This calls for urgent attention to future water allocation planning, management and monitoring to ensure sustainable resource use and to avoid building infrastructure that fails to deliver on expected investment returns.

The pattern of diminishing irrigation infrastructure investment returns is also demonstrated in Figure 16. When the area under modern agriculture equipped with irrigation facilities doubles from 20% to 40%, unmet demand for irrigation doubles. At the same time, however, water supply to crops only increases by approximately 10%. In total, the annual unmet demand by 2050 in the Optimistic scenario amounts to about 22.5 km^3 per year, which can be compared with an approximate water availability for the study area

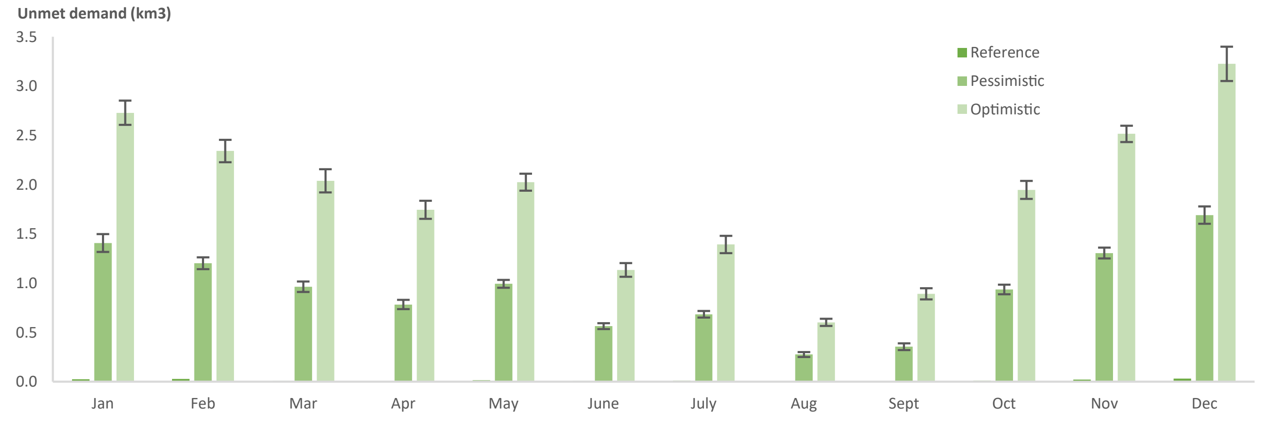
Figure 15. Average unmet demand/demand for hydropower and irrigation, 2036-2050



Note: Error bars denote the values for dry and wet climate sub-scenarios for each development scenario. Solid bar represent average values across dry and wet climate sub-scenarios.

of 19 km^3; i.e. the total unmet demand exceeds water availability on an annual basis. In addition, out of the total available water, only 6.7 km^3 is available as surface water in rivers and lakes and groundwater, whilst the rest is held in the soil profile. Thus, only a third of the unmet demand for irrigation could theoretically be met if irrigation infrastructure was expanded by 40%. In other words, in the "Optimistic" scenario we equip fields with irrigation infrastructure, but it is impossible use that infrastructure because there simply is not enough water. Future irrigation schemes should be planned according to basin capacity, and should focus specifically on options that would improve irrigation efficiency and reduce crop water demands.

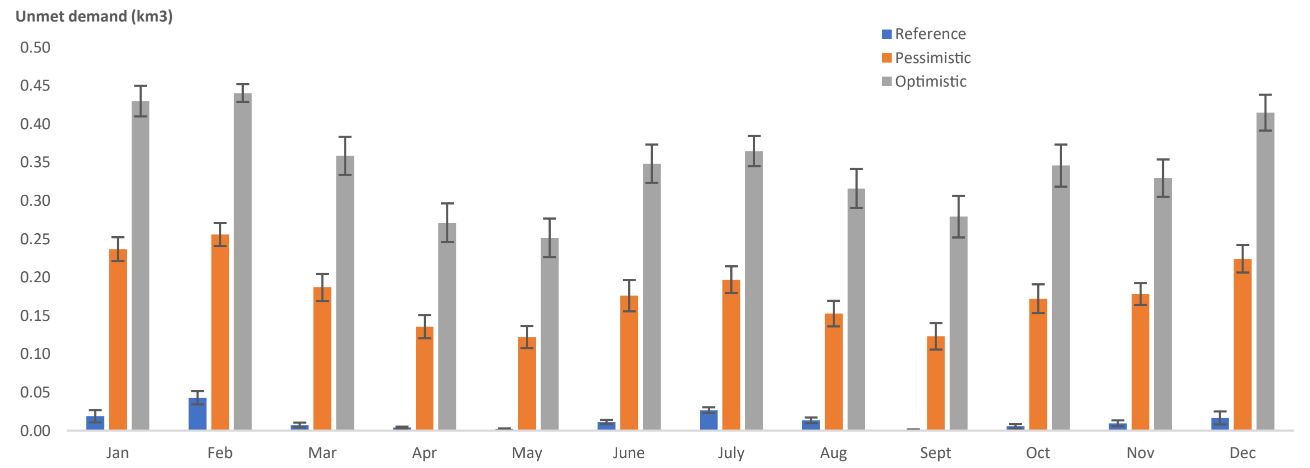
Figure 16. Average irrigation unmet demand, 2036-2050



Note: Error bars denote the values for dry and wet climate sub-scenarios for each development scenario. Solid bars represent average values across dry and wet climate sub-scenarios.

Similarly, hydropower generation is strongly limited by water availability. Higher water demands for hydropower production in the Optimistic scenario due to the drive in national plans for more installed capacity leads to a doubling of unmet water demands, compared to the Pessimistic scenario (Figure 17). This sheds light on some of the challenges of sustainable resource use in national energy and agriculture plans, where there is often competition over water use. Again, comparing with the approximate water availability for the study area of 19 km^3 (6.7 km^3 is blue water), the total annual unmet demand by 2050 in the Optimistic scenario amounts to about 4.5 km^3 per year. This is arguably a lot less than the corresponding future for irrigation, but it is still very high in relation to the water availability. Since irrigation takes priority over hydropower production in terms of water abstractions, the interannual variation in unmet demands looks slightly different between hydropower and irrigation. We also conclude in this case that it is pointless to add more run-of-river turbines unless we re-prioritise water use. Indeed, much more coordinated planning on infrastructure development between the energy and agriculture sectors is essential to ensure water resources are managed effectively in the future.

Figure 17. Average hydropower unmet demand, 2036-2050



Note: Error bars denote the values for dry and wet climate sub-scenarios for each development scenario. Solid bar represent average values across dry and wet climate sub-scenarios.

Figure 18. GHG emissions from energy use in all sectors across all scenarios

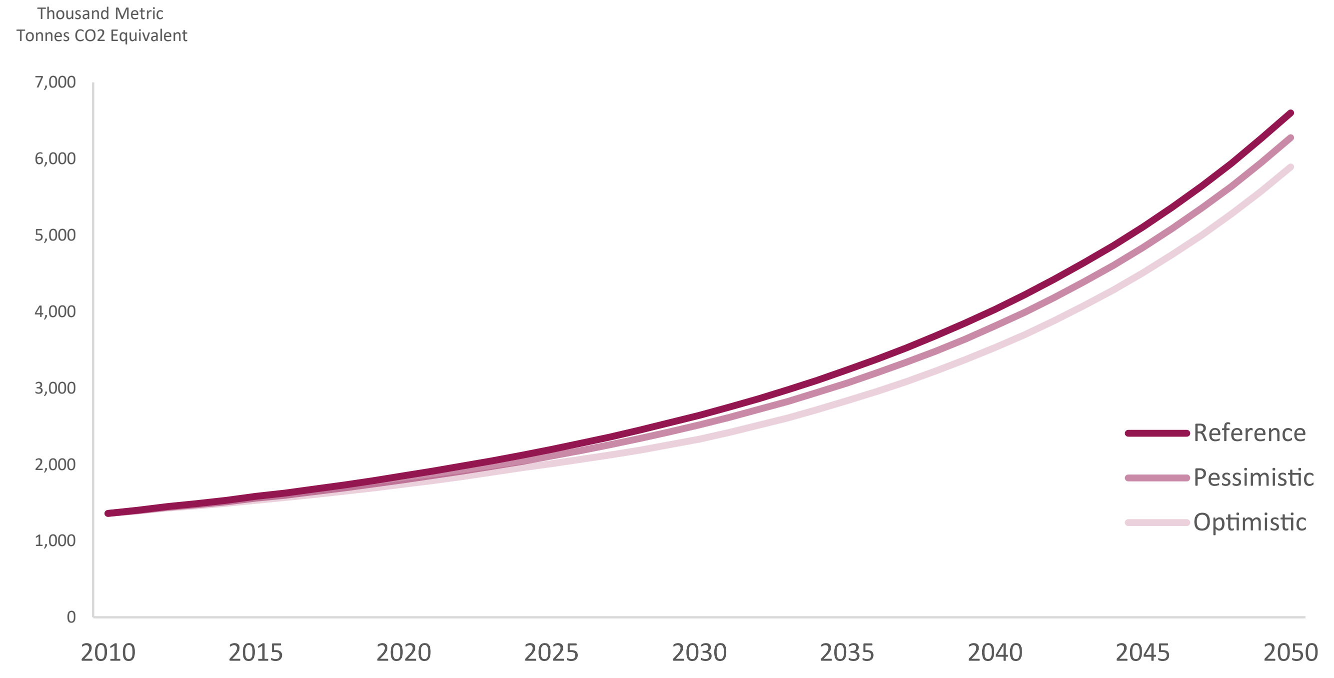
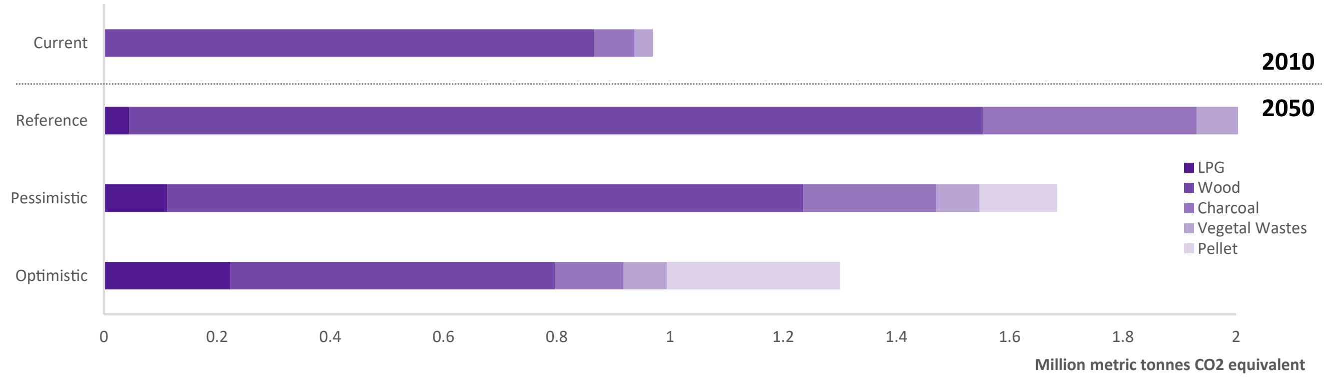


Figure 19. Different cooking fuel GHG emission scenarios in 2010 and 2050



Reducing greenhouse gas (GHG) emissions within the energy sector forms part of Rwanda's commitment to global climate change mitigation. Figure 18 shows that in all scenarios GHG emissions increase considerably as energy supply grows to meet the rising demands of a growing population, and as peat becomes a major source of electricity generation. The figures were generated by LEAP using standard GHG emission data for different fuels and technologies. Despite the increase in overall emissions, there is a 5% and 10% reduction in the Pessimistic and Optimistic scenarios respectively compared to the Reference scenario. These reductions are the result of interventions to promote greater use of alternative cooking fuels and technologies in both scenarios, with more extensive interventions assumed in the Optimistic scenario, as shown in Figure 19. In addition, in the Pessimistic scenario we assumed that biomass was harvested according to demand, with no constraints on sustainability of the resource; whereas in the Optimistic scenario we sought to model sustainable use of biomass by constraining the model such that biomass harvesting was limited to 70% of the annual increase in woody biomass (i.e. net primary productivity of forests and shrubland).[2] In the Reference scenario, GHG emissions from cooking fuels more than doubled between 2010 and 2050; from 970 $MtCO_2e$ to 2000 $MtCO_2e$. In the Pessimistic scenario, in which there is limited switching of cooking fuels, GHG emissions only rise to 1680 $MtCO_2e$ by 2050. And in the Optimistic scenario, where switching of cooking fuels is more extensive, GHG emissions only rise to 1300 $MtCO_2e$. More efforts in other sectors are clearly needed to make a significant difference in overall GHG emissions.

4.4 Implications of the results

Achieving a sustainable transition in the energy sector, including the distribution of new technologies and fuels to a growing population, will require considerable effort. According to our findings, energy demand may be two to three times higher in 2050 than today. Moreover, our results indicate that Rwanda may need to import electricity by 2040 to meet rising demand. The earlier it needs imports, the larger they are likely to be. This will depend on how fast the country reaches universal electricity access. This scenario can provide an opportunity for greater regional power trade, if political challenges can be addressed. Hydropower is likely to continue to play an important role in a growing energy portfolio. Our policy coherence analysis in Section 3 indicated, however, that there may be conflict between the goals of transforming agriculture, which involves irrigation expansion, and higher hydropower production. According to our modelling, hydropower constitutes approximately 40-50% of the total energy generation, both now and in the 2050 scenarios. Our quantitative analysis on water resources availability shows that the reason why the share of hydropower is not larger in the future is because of severe water restraints. If hydropower infrastructure is expanded according to the national policy framework, a large part of it will not be used. A limitation of this current study is that all options for expanding energy generation and potential demand management options have not been explored. For instance, it would be interesting to investigate the potential to expand solar power and the utilization of industrial waste such as sugar cane for energy production, as well as to analyse options to improve energy efficiency in the industry sector.

Transforming agriculture and increasing production is likely to be constrained by resource availability, predominantly water, in the future. Our scenario analysis indicates that even when 40% of current agricultural land is converted from traditional to modern farming, total food demands will exceed supply by a factor two by 2050. However, these results should be evaluated cautiously, as we may have overestimated the impact of water availability in relation to nutrient stress. This would lead to crop production underestimation in future scenarios that simulate the impact of agricultural transformations. The policy analysis revealed that universal energy access will enable, or possibly even reinforce, the transformation process. As Rwanda is facing electricity imports, however, the transformation process could be negatively impacted due to potentially higher costs. Moreover, the policy process showed a potential conflict between water use for hydropower production and irrigation. In this study, agriculture took preference over hydropower, and thus irrigation is not impacted by additional hydropower infrastructure.

This study showed that in all future development scenarios, pressure on both land and water ecosystems will remain high, driven by high population growth and a changing climate. Even in the most optimistic scenario, where concerted attempts are made to replace biomass as one of the main sources of cooking fuel, demand for fuel wood is twice as high as supply. As a result, the prospect unsustainable forest biomass use continues to pose a high risk of deforestation and forest degradation, which is contrary to

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[2] 30% of net primary productivity was returned to the soil to maintain essential ecosystem services.

Farming Rwanda’s hilly landscape © Philbert Nsengiyumva / ARCOS

the policy coherence analysis initial findings. In addition, a significant portion of future energy production is expected to be generated from peat, and approximately 100 000 ha of wetlands are planned for conversion to agricultural land, posing a major threat to wetland ecosystems.

As revealed in the policy coherence study, there is a potential conflict between the increased water demand needed to fuel the transformation processes, and the need to preserve water to meet environmental flow demand. Our estimations indicate that if approximately 40% of agricultural land is equipped with irrigation facilities, unmet irrigation demand could amount to as much as 80% of total demand on an annual basis. Our model simulations put the highest priority for water allocations on meeting environmental flow requirements and domestic water needs. In practice, however, the competition between irrigation and hydropower production is likely to be strong, and the risk for water over-abstraction, with concurrent negative impacts on groundwater and limnic and wetland ecosystems, is significant. As the policy coherence analysis revealed, the intensification of agriculture also poses an additional threat to these ecosystems by potentially leading to higher sedimentation, nutrient leaching, and pollution from higher herbicide and pesticide use. These factors, however, where not analysed quantitatively.

Our modelling results show that GHG emissions can be reduced by increased adoption of cleaner cooking fuels and technologies. However, significant efforts are needed in other sectors to reduce emissions further to be in line with global climate change mitigation commitments. In the electricity sector, GHG emissions reductions due to decreased use of diesel are likely to be reversed by much greater use of peat. In addition, private transport use may also increase as the population and economy grows, which will put additional pressure on emissions. We believe further research is needed to better understand the GHG implications of Rwanda’s development pathways.

In conclusion, the significant competition for Rwanda’s limited resources threatens to constrain social and economic development, as well as environmental sustainability. This calls for 1) strategic resource allocation planning at the central level to develop policies and policy mechanisms that lead to meeting national targets and avoid negative externalities, 2) platforms for multi-stakeholder involvement and dialogue, and 3) implementation of technologies that enable sustainable and efficient resource use.

5. Managing natural resources at the district level

It remains a major challenge of how to translate national priorities and strategies into local action remains. In this section, we explore development challenges and opportunities in three districts in Rwanda – Rutsiro, Bugesera and Kirehe – each with differing landscapes. We draw on an integrated landscape monitoring survey carried out in each district from February to April 2016, and perspectives and opinions of key stakeholders and community representatives collected during workshops held in May and August 2017.

5.1 Challenges at the district landscape level

Rutsiro, Bugesera and Kirehe lie within the Akagera basin, a 60 500 km2 watershed stretched across parts of Burundi, Rwanda, Tanzania and Uganda. As the landscape shifts from the forest-covered mountains of Rutsiro to the hilly savannahs of Bugesera, to the low plateau savannah of Kirehe, the Nyabarongo and Akagera Rivers act as major arteries supporting life and economic activity. Agriculture – the main economic activity in all three districts – is largely rain-fed and based around traditional farming practices (e.g. there are three tractors in Kirehe District). More than 15 potential sites for small run-of-the-river hydropower plants ranging between 100kW to 1MW have been identified upstream, whilst downstream at Rusumo Falls a larger run-of-the-river hydropower plant is currently under construction.

All three districts have a similar number of people, and in each around half of the population is considered poor, one third do not have access to clean water, and 96–99% do not have access to electricity. Correspondingly, the major challenges in all three districts are water, energy and food security, although their root causes often differ due to geographical diversity.

- **Water:** The scarcity of clean drinking water in Rutsiro is a result of the difficulty of building infrastructure in hilly terrain. In Bugesera and Kirehe there is a lack of water treatment plants, (although Bugesera is currently building an additional plant). Water pollution in Rutsiro is largely a result of extensive coltan mining, whereas pollution in Bugesera and Kirehe stems from agricultural farming on fertile riverbanks. The scarcity of clean drinking water in all three districts has severe health implications, such as increased risk of waterborne disease outbreaks, diarrhoea, and other regular incidences of preventable illnesses. These health concerns are exacerbated by limited health facilities.
- **Energy:** Electricity connectivity rates are low, and 95–97% of families rely on firewood for cooking and heating. Scarcity of firewood and a demand that is exceeding sustainable supply is contributing to forest degradation, as well as families having to allocate a lot of time for firewood collection that could have been spent more productively. Compounding these issues, local charcoal production to meet demand for cooking fuel in urban areas – alongside clearing of land for agriculture – is responsible for the majority of deforestation and degradation in the three districts.
- **Food:** Food productivity is low and exacerbated by adverse climate variability. Farming practices in all landscapes are largely traditional, small-scale and un-mechanized, with regular use of chemical fertilizers, limited irrigation and scattered attempts to control soil erosion. Most farmers have limited revenue and are thus typically unable reinvest to up- grade their farms. Agricultural land clearing is a significant contributor to deforestation and forest degradation. Farming productivity may be further limited by soil degradation if the extraction of organic matter and nutrients is made more unsustainable by growing resource scarcity (e.g., see Karlberg et al. 2015)
- **Environment and landscapes:** In Rutsiro, intense deforestation and clear-cutting, as well as widespread traditional agricultural practices including extended periods of bare soil conditions, creates high vulnerability to erosion, land degradation and landslide risk during the rainy season. In Kirehe, flooding and drought are prevalent challenges to local communities, and erosion upstream has led to a high level of sedimentation downstream. In Rutsiro and Bugesera, charcoal and woodfuel supply to Kigali – where roughly 70% of residents use charcoal for cooking (see Drigo et al. 2013) – contributes to deforestation and forest degradation, both of which are also exacerbated by small-scale timber production in the area.

5.2 Visioning in the district landscapes

Each of Rwanda's 30 districts formulated District Development Plans setting out their contributions to achieving the national development targets set out in EPDRSII. The plans set out similar overarching priorities to address common issues faced in all district landscapes, such as transforming agriculture, encouraging the use of alternative energy sources, promoting tourism and education and developing infrastructure and off-farm business opportunities (see Republic of Rwanda 2013a; 2013b; 2013c). Below we emphasize the interconnectedness of the regions' issues and highlight ways to address them at local and national level.

5.2.1 Local needs

In the workshops held in each district, local experts identified needs required to achieve their visions for their districts. While some are clearly location specific, others are of a more general nature and could apply to the country as a whole.

In all three districts, improved water management was considered critical for sustainable, secure and efficient use of water resources for all sectors. In addition, an array of technical options to enhance water supply and quality were identified, such as wastewater treatment plants, an improved supply infrastructure, and rainwater capture for agriculture.

To increase access to electricity, and its affordability and reliability, participants in all three districts pointed to the importance of diversifying options for electricity generation and developing off-grid solutions. Local experts raised the pressing need to replace traditional cookstoves and fuels with cleaner and more efficient alternatives to reduce negative health impacts and improve fuel efficiency.

Several low-cost technological options were identified for agriculture, such as terracing, use of manure as fertiliser, and water harvesting solutions, all of which potentially will have positive impacts on resource use and sustainability. At the same time, local experts noted that limited technology, low awareness and poor access to finance were considerable barriers to agricultural transformation in Rwanda's districts. It is clear that deforestation remains one of the major pressures facing all three landscapes. Many pro- posed actions to address it related to tree plantations and agroforestry: for example, experts in Rutsiro stated that raising community awareness on terracing and tree planting programmes is critical for saving the district's natural habitat. However, growing urban demand for charcoal as a cooking fuel is a major cause of deforestation, which means that increasing the supply of woody biomass will not suffice: it will also be necessary to shift demand from charcoal to alternative energy sources. In addition, agricultural expansion and intensification continues to add further pressure on land resources.

The lack of available land for producing fuel and food is clearly a barrier to sustainable development in Rwanda. Part of the solution would be to reduce dependence on charcoal for cooking in urban centres. This would enable the conversion of woodfuel tree plantations into agricultural land, thereby reducing pressure on forests caused by agricultural expansion. The question remains as to what would be the most effective long-term use of land in the districts to ensure both forest ecosystem health and human well-being.

5.2.2 National support for local needs

To address needs at the local level and ensure coordinated action on issues that are common to multiple districts, we identify a range of actions that can be initiated by the national government, and which could apply broadly across all districts in Rwanda. These include creating an enabling environment, providing financial support and providing infrastructure and services, and ensuring access to knowledge services. Many of these actions and enabling conditions would require large financial investments by the state directed at those smallholder farmers that have limited access to other means of finance. Increasing pressures from a changing climate and a rapidly growing population adds to the urgency of the situation.

There is a critical need to create policies and incentives to encourage use of more sustainable cooking fuels in order to combat deforestation and degradation. For example, char- coal is produced in the districts but mainly supplies urban areas, so the promotion of sustainable cooking fuels needs to be tackled at the national level. The new biomass energy strategy that is under development could help to address these issues. Finally, there is a need for improved resource planning (i.e. water, land and biomass) at the national level to underpin national development targets.

6. Conclusions and recommendations

In this report, we have applied SEI's 'nexus toolkit' to explore the water-energy-food nexus in Rwanda at the national and district levels. We used our toolkit to analyse policy coherence, biophysical interlinkages and district visions through a participatory approach with stakeholders from different sectors.

Our policy coherence analysis highlighted potential hotspots where resource use competition between sectors might flare up as resources become increasingly scarce. For example, it was clear that achieving energy transition goals might constrain certain agricultural transformation objectives – particularly if water for hydropower was prioritised over water for irrigation – but others might be reinforced through increased energy access. Similarly, achievement of agricultural transformation objectives could constrain hydropower generation if irrigation water is allocated to upstream fields, but higher agricultural production might lead to more agricultural residues that could be used for biogas or pellet production.

Our quantitative assessment sought to dig deeper into some of these potential synergies and conflicts around natural resource use by modelling development pathways related to the water, food and energy sectors up to 2050. These pathways corresponded to business-as-usual practices (Reference scenario), weak implementation of national plans (Pessimistic scenario) and full implementation of national plans whilst ensuring sustainable use of natural resources (Optimistic scenario). All scenarios included two climate change sub-scenarios related to a dryer or wetter climate. Our modelling – undertaken in tandem with a team of technical experts in Rwanda – showed that in all future development scenarios, pressure on land, biomass resources and water ecosystems continues to remain severe, driven by high population growth and a changing climate. Even in the Optimistic scenario, where a concerted effort is made to replace biomass as a main source of cooking fuel, the demand for fuel wood is still twice as high as supply. As a result, the prospect of unsustainable forest biomass use continues to pose a high risk for deforestation and forest degradation, which is contrary to the policy coherence analysis initial findings. In addition, a segment of future energy production is expected to be generated from peat, and approximately 100 000 ha of wetlands are planned for conversion to agricultural lands, posing a major threat to wetland ecosystems.

Farming near the buffer zone at the banks of the Akagera river © ARCOS

This ongoing competition for limited resources calls for more strategic resource allocation planning at the central level to: develop policies and policy mechanisms that lead to meeting national targets and avoid negative externalities; establish platforms for multi-stakeholder involvement and dialogue; and implement technologies that enable sustainable and efficient resource use. Our district visioning exercise highlighted the importance of coordinated action on issues that are common to multiple districts at both national and district levels. Local actions in the districts from farmers, conservationists, businesses and stakeholder groups can be more effective with robust financial support and increased knowledge, infrastructure and services support at the national level.

Rwanda's ambition to pursue a climate resilient green growth development pathway are laudable. Already, significant work is underway to make this pathway a reality. However, the disconnect between sectors at the national and district levels poses a considerable long-term threat to sustainable resource use and ecosystems preservation. Without more strategic planning, multi-stakeholder dialogue, upscaled support to disseminate existing solutions, and continued landscape monitoring and evaluation, the country may squander its natural resources, which are vital to the prosperity of future generations.

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Appendix A. Data and assumptions used in the modelling tools

In Table 1 below we set out the data and assumptions used as inputs into the LEAP and WEAP modelling software tools.

Table 1. Data and assumptions input into WEAP and LEAP

Sector	Current accounts in 2010[a]	Scenario in 2050[b]		
		Reference	Pessimistic	Optimistic
Economy and demographics[c]				
Average GDP growth	7.9%[d]	7.9%	7.9%	7.9%
GDP share				
Public service sector	25.3%			
Commercial and industrial sectors				
Agriculture and fisheries	22.0%			
Manufacturing	5.6%			
Other commercial	47.1%			
Population[e]				
Size	10.5 million			
Growth	2.5%	2.5%	2.5%	2.5%
Density (ppl/ km^2)	416			
Urban-rural population split	17:83			
Urban-rural household split	16.5:83.5			
Poverty rates				
Urban	22.1%			
Rural	48.7%			
Climate and ecosystems[f]				
Precipitation (mm/yr)	1300			
Future change (%)	+/-10%			
Temperature (°C)	19.6			
Future change(°C)	+3°C			
Humidity (%)	12.3			
Environmental flow requirements[g]	30%	Low priority	Low priority	High priority
Irrigation demand		Medium priority	Medium priority	Medium priority
Hydropower water demand		Low priority	Low priority	Low priority
Domestic water demand		High priority	High priority	High priority
Soil types	Shallow soil with low water retention capacity in head-flow catchment; sandy clay loam in valley catchment			
Land use and agriculture[h,i]				
Forest land area (ha)	671 000			
Plantation (ha)	287 000			+30% (+86 100 ha)
Closed natural forest (ha)	108 000			
Degraded natural forest (ha)	12 600			

Sector	Current accounts in 2010a	Scenario in 2050b		
		Reference	Pessimistic	Optimistic
Natural shrubs (ha)	260 000			-30% of area of forest plantations (-86 000 ha)
Wooded savannah (ha)	1 770			
Agricultural land area (ha)	1690 000			
Cropland (ha)	1 370 000			+100 000 ha
Maize (%)	11.5			
Sorghum (%)	2.4			
Cereal (%)	1.2			
Cassava (%)	19.5			
Sweet potato (%)	4.4			
Irish potato (%)	3.7			
Banana (%)	18.3			
Green bean (%)	12.1			
Legumes (%)	3.4			
Vegetables (%)	1.1			
Fruit trees (%)	0.6			
Tea (%)	1.0			
Coffee (%)	2.0			
Meadow and pasture (ha)	322 000			-100 000 ha
Urban land area (ha)	19 100			
Agricultural practices[j]				
Low inputs (“traditional”)				
Total cropland area (%)	98	98	80	60
Productivity	0.5 LAI	0.5 LAI	0.5 LAI	0.5 LAI
High inputs (“modernised”)[l]				
Total cropland area (%)	2	2	20	40
Productivity	LAI	LAI	1.05 LAI	1.25 LAI
Net primary productivity[k]				
Forests (t dm/ha/yr)				
Forest plantation	16	1.0 LAI	1.05 LAI	1.25 LAI
Closed natural forest	16			
Degraded natural forest	12			
Bamboo	10			
Natural shrubs	5			
Wooded savannah	13			
Agriculture				
“Traditional” crop yields (t dm/ha/yr) / number of crops per year				
Maize	1.24 / 2			
Sorghum	0.83 / 2			
Cereal	0.74 / 2			
Cassava	0.49 / 2			
Sweet potato	1.80 / 2			
Irish potato	1.40 / 2			
Banana	0.84 / 1			
Green bean	0.10 / 2			
Legumes	0.42 / 2			

Sector	Current accounts in 2010[a]	Scenario in 2050[b]		
		Reference	Pessimistic	Optimistic
Vegetables	0.66 / 2			
Fruit trees	0.38 / 1			
Tea	1.50 / 1			
Coffee	0.50 / 1			
Meadows and pastures	6.0			
Urban (t dm/ha/yr)	0.23			
Energy[m]				
Electricity access (% of population)	16%			
Urban	67%	67%	100%	100%
Rural	6.4%	6.4%	100%	100%
Total electricity generation (GWh)	281.17			
Electricity generation by source (% share)				
Diesel	56.9%			
Hydropower	39.8%			
Solar	0.1%			
Methane	3.2%			
Cookstove penetration (% share of hhs)[c]				
Urban wood stoves				
Fixed improved mud stove	35.1	35.1	20	0
Mud stove	12.6	12.6	10	0
Potable improved mud stove	4.5	4.5	0	0
Three-stone stove	30.4	30.4	20	0
Improved wood stove	17.3	17.3	10	0
Tier 3 wood stove	0	0	15	40
Pellet gasifier	0	0	25	60
Urban charcoal stoves				
Single-pot metal charcoal stove	61.9	61.9	0	0
Multi-pot metal charcoal stove	30.4	30.4	20	0
Camanake ivuguruye	6.3	6.3	30	60
Improved single pot charcoal stove	1.3	1.3	40	0
Modern charcoal	0	0	10	40
Rural wood stoves				
Fixed improved mud stove	35.9	35.9	20	0
Three-stone stove	32.4	32.4	0	0
Improved wood stove	26.8	26.8	20	0
Mud stove	3.7	3.7	0	0
Portable improved mud stove	1.2	1.2	20	0
Tier 3 wood stove	0	0	30	70
Pellet gasifiers	0	0	10	30
Rural charcoal stoves				
Single-pot metal charcoal stove	63.6	63.6	50	0
Multi-pot charcoal stove	19.4	19.4	10	0
Improved single-pot charcoal stove	9.1	9.1	5	0
Canamake ivuguruye	7.8	7.8	25	60
Modern charcoal	0	0	10	40
Primary fuel for cooking (% share of hhs)				

Sector	Current accounts in 2010[a]	Scenario in 2050[b]		
		Reference	Pessimistic	Optimistic
Urban				
Firewood and pellets	31.4	31.4	27.9	22.5
Charcoal	62.7	62.7	42.3	22.7
LPG	1.1	10	25	50.0
Electricity	0.7	0.7	0.7	0.7
Biogas	0.1	0.1	0.1	0.1
Others	4.0	4.0	4.0	4.0
Rural				
Firewood and pellets	92.6	86.8	77.9	62.9
Charcoal	2.9	2.9	2.9	2.9
LPG	0.1	4	10	20.0
Electricity	0.1	0.1	0.1	0.1
Biogas	0.1	2	5	10.0
Others	4.3	4.3	4.1	4.1
Mechanisation (128 l diesel/ha)	5% of high input cropland	5% of high input cropland	15% of high input cropland	50% of high input cropland
Fertiliser use (kg/ha/yr)	8			45 (by 2020)

dm = dry matter, ha = hectares, hh = household, l = litre, LAI = leaf area index, LPG = liquefied petroleum gas, t = metric ton

Notes

[a] *In both WEAP and LEAP models, 2010 was chosen as the base year to provide a statement of "current accounts". In WEAP, historical data for 1971–2014 was used; in LEAP historical data for 2005–2010 was used.*

[b] *Numbers in each scenario represent the data and assumptions used as inputs in the model to define the particular development pathway.*

[c] *See https://data.worldbank.org/*

[d] *Based on average data for 2000–2016.*

[e] *Based on data for 2012.*

[f] *Smakhtin (2008) and Republic of Rwanda (2013d)*

[g] *Percent of mean annual flows.*

[h] *Figures here represent the whole of Rwanda. Only 60% of these values were included in the Akagera catchment area modelled in WEAP, split across all catchments proportional to areas in sub-watersheds. Land-use changes in the optimistic scenario start in 2020, end in 2030 and remain constant from then onwards.*

[i] *Land use based on Drigo et al. (2013), NISR (2016), https://data.worldbank.org/ and http://www.fao.org/faostat/en/#data. There is a high degree of variation between land-use data sets.*

[j] *Agricultural practices based on Republic of Rwanda (2012), NISR (2016), Ministry of Agriculture and Animal Resources (2009).*

[k] *Net primary productivity based on Cao and Woodward (1998), Moore et al. (2018) and Scurlock et al. (2002).*

[l] *Irrigation takes place on these lands when the soil moisture is not enough to meet plant water demands, and there is water available for irrigation*

[m] *The LEAP model was downscaled to match the WEAP model of the Akagera catchment. By overlaying a Rwanda population map onto the Akagera catchment map, we were able to estimate that the catchment area contained 72% of Rwanda's total population. For household energy demand in LEAP, the population was determined as 72% * (total population – 75% boarding school and 50% university students). By conservative estimates, boarding school students make up a majority of secondary school students, whereas around half of students at university reside there. In order to avoid double counting, they were subtracted from the population when determining household demand and instead their energy consumption contributed to public service sector energy demand. Data was compiled from Republic of Rwanda (2013d), Drigo et al. (2013), Ministry of Infrastructure (2013), Africa Energy Services Group (2012), NISR (2012a) and NISR (2012b).*

[n] *These figures were calculated by combining data on cooking fuels and cooking technologies.*

Parameterisation and calibration of the WEAP model

Crop yields in "current accounts" were estimated by initially using the parameter values for each crop type in the WEAP crop library. Since those values were derived from crops grown under high input conditions in the United States, the leaf area index (LAI) related parameters were adjusted to 50% of their original value (Table 1, agricultural practices/low inputs/productivity). Subsequently, the harvest index of each crop was modified so that the crop yields under low input/traditional management matched measured values (Table 1, croplands/yields). The derived harvest indices were then also used for high input/modernised land-use areas, for all scenarios; that is, the harvest index remained the same in all scenarios. Instead, to estimate differences in yields as a function of management, the LAI-related parameters in the crop library were adjusted (Table 1, agricultural practices/productivity) to depict the effect of the different management regimes.

The hydrology module of WEAP was calibrated using measured stream flow data from stream gauges throughout Rwanda, by modifying the hydraulic conductivity for the two soil types described in the table above (Table 2). Because of the high uncertainty in measurements, a relatively high deviation between simulated and measured stream flows was deemed acceptable.

Table 2. Comparison between modelled and simulated stream flows

Stream-flow gauge station	Modelled (M)/ Observed (O)	Mean	Standard deviation	RMS
Mwogo / Nyabisindu	M	9.3	8.0	12.3
	O	5.5	3.0	6.3
Nyabarongo / Mwika	M	49.0	31.6	58.3
	O	37.8	14.5	40.5
Nyabarongo / Nagaru	M	84.4	51.8	99.0
	O	68.0	18.5	70.4
Nyabarongo / Kigali	M	48.4	30.8	57.3
	O	94.5	33.5	100.2
Nyabarongo / Rifune	M	207.8	115.3	237.4
	O	131.6	31.1	135.2
Nyabarongo / Risumu	M	257.7	78.1	269.2
	O	339.0	216.4	401.8

Linking WEAP and LEAP

Annual hydropower production was estimated by WEAP and used as input in LEAP in all scenarios. In addition, in the optimistic scenario 80% of the WEAP values for annual increment (net primary productivity) in forest biomass and 80% of WEAP values for crop residues were used as an input in LEAP for woody biomass available to meet demand for woodfuel and charcoal and crop residues available to meet demand for pellets. Thus, 20% of the net primary productivity in forest biomass and 20% of crop residues were left in the ecosystems to ensure a sustainable withdrawal of biomass for energy.

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