TRANSITION PATHWAYS AND RISK ANALYSIS FOR CLIMATE CHANGE POLICIES

TRANSITIONS PATHWAYS AND RISK ANALYSIS FOR CLIMATE CHANGE MITIGATION AND ADAPTATION STRATEGIES

Prospects for Hydropower in Ethiopia: An Energy-Water Nexus Analysis

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Preface

Both the models concerning the future climate evolution and its impacts, as well as the models assessing the costs and benefits associated with different mitigation pathways face a high degree of uncertainty. There is an urgent need to not only understand the *costs and benefits* associated with *climate change* but also the *risks, uncertainties and co-effects* related to different *mitigation pathways* as well as *public acceptance* of low-carbon (technology) options (or lack thereof). The main aims and objectives of TRANSrisk therefore are to create a novel assessment framework for analysing costs and benefits of transition pathways that will integrate well-established approaches to modelling the costs of resilient, low-carbon pathways with a wider interdisciplinary approach including risk assessments. In addition *TRANSrisk* aims to design a decision support tool that should help policy makers to better understand uncertainties and risks and enable them to include risk assessments into more robust policy design.

PROJECT PARTNERS

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1	Science Technology Policy Research, University of Sussex	SPRU	UK	
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5	Swiss Federal Institute of Technology (funded by Swiss Gov't)	ETH Zurich	CH	
6	Institute for Structural Research	IBS	PL	
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1 PROSPECTS FOR HYDROPOWER IN ETHIOPIA: AN ENERGY-WATER NEXUS ANALYSIS

In this paper we investigate the prospects for large-scale hydropower deployment in Ethiopia. Ethiopia has ambitious plans for bolstering economic growth and aims to fulfil much of the associated energy requirements by exploiting its large estimated domestic hydropower potential. Important benefits of this abundant energy resource are that it allows for stimulating economic development, increasing energy access, and alleviating poverty, while simultaneously avoiding concomitant emissions of greenhouse gases, particularly CO_2.

In this study we address the question of what the desirable level of hydropower use in Ethiopia could be until 2050, and inspect whether that level is practically feasible. For this purpose we employ the combination of two models, TIAM-ECN (an energy systems models) and RIBASIM (links hydrological water inputs with water-users), to allow for two distinct sectoral perspectives. They enable, respectively, a detailed energy systems analysis through a cost-minimisation procedure, and a river basin water balance assessment under varying conditions concerning surface water supply and water demand by the domestic and agricultural sectors.

Through these two different approaches we find high projections for future hydropower generation in Ethiopia: between 71 and 87 TWh/yr by 2050 in a stringent climate change control scenario in which Ethiopia contributes substantially to global efforts to reach the 2°C target fixed in the Paris Agreement. This elevated level is obtained despite expansions in domestic and irrigated agriculture water demand and irrespective of hydrological effects from climate change in terms of a drop in average precipitation at the national scale. This amount of hydro-electricity production matches the expected national hydropower potential.

Based on our cost-optimisation and technical feasibility assessment, we provide insights on Ethiopia's ambitious hydropower development plan. We also encourage further research in the area to take due account of the large impact that climate change may have on rainfall during some months at the local level, as well as social and environmental impacts that result from large scale hydropower development.

1.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has published voluminous reports on the large-scale deployment of renewable forms of energy to achieve deep cuts in greenhouse gas (GHG) emissions, with the aim of mitigating global climate change (IPCC, 2011; IPCC, 2014). In recent years increasing attention has been paid to emissions reduction requirements at the regional level, in view of staying well below the 2°C average global temperature increase fixed in the Paris Agreement (COP-21, 2015): for recent studies on Asia, Africa and Latin America, see e.g., respectively, Calvin et al. (2012), Lucas et al. (2015), and van der Zwaan et al. (2016a). Africa occupies a special place among these developing regions, since it is exceptionally rich in energy resources, but poor in energy supply, notably in Sub-Saharan Africa (IEA-WEO, 2014). According to the International Energy Agency (IEA): “Making reliable and affordable energy widely available is critical to the development of the [Sub-Saharan] region that accounts for 13% of the world’s population, but only 4% of its energy demand” (IEA-WEO, 2014). This article contributes to the growing literature on how modern forms of energy can be supplied to Africa while controlling climate change through low-emission development strategies (LEDS), by analysing its second most populous country, Ethiopia.

Under the Paris Agreement all countries committed to realise substantial GHG emission reductions in the short term (COP-21, 2015). Ethiopia’s ambitions are particularly significant under its Nationally Determined Contribution (NDC), as it intends to reduce its projected business-as-usual emissions in 2030 by 64%, implying a decrease of 255 $MtCO_2e$ from the estimated baseline figure of 400 $MtCO_2e$ down to 145 $MtCO_2e$ (INDC-Ethiopia, 2015). Of this total GHG emissions reduction figure, 130 $MtCO_2e$ is realised in forestry and 90 $MtCO_2e$ in agriculture, with the remaining 35 $MtCO_2e$ materialised through a combination of GHG abatement efforts in transportation, industry and buildings. The power sector is projected to remain at its current emission level of 5 $MtCO_2e$, even while a large expansion is foreseen for the generation of electricity in order to expand access to this modern form of energy in the country. Wind and geothermal power are both low-carbon energy options with large potentials in Ethiopia, but hydropower has been recognised for decades as the single most valuable power production option in the country. The existence of large rivers flowing in deeply incised valleys provides attractive conditions for medium- to large-scale hydropower plants, with an overall national potential of perhaps as much as 45 GW (MWE, 2011). Today about 2 GW of hydropower capacity is in operation in Ethiopia, and construction is underway to multiply this level five-fold over the next several years. In its 25-year development plan the Ethiopian Electric Power Corporation (EEPCO), the government’s national utility responsible for power generation, transmission, distribution and sales of electricity, plans to massively expand this capacity over the decades to come (MWE, 2011). Our purpose is to shed light on the economic and technical feasibility of such a large role for hydropower in Ethiopia’s electricity generation system.

It is estimated that Ethiopia is endowed with about 140,000 Mm^3/yr of freshwater resources, of which about 86% are surface freshwater resources. The Blue Nile constitutes the largest river basin in the country, where about 70% of its surface freshwater resources can be found. Within the Blue Nile, three main river systems can be distinguished: the Abbay, Baro-Akobo and Tekeze, which represent, respectively, 44%, 20% and 6% of the national freshwater resources of Ethiopia. These river systems together have an estimated average annual water discharge of about 117,000 Mm^3/yr.

In this paper we investigate the large-scale use of hydropower in Ethiopia from a cost-optimality perspective. We also analyse it from a hydrological point of view for the Blue Nile river system in Ethiopia, and inspect the multiple effects of population growth as well as the future variability and possible vulnerability of hydro-electricity generation due to the impacts of climate change. On the basis of the country level distribution of water resources and the foreseen national plans for hydropower development, we extrapolate our results for the Blue Nile to the national level.

With this study we connect to studies with a global focus on the challenges of renewable energy deployment (GEA, 2012; IEA-ETP, 2016). We contribute to work undertaken to address the question of how to provide “sustainable energy for all” in Africa (UN, 2012). By focusing on the use of hydropower and its ramifications in Ethiopia we make a deep-dive into the water-energy-food nexus discussion (IRENA, 2015). Given the size of required emission cuts world-wide, the contribution from hydropower in national mitigation efforts is drawing renewed interest, particularly in developing countries (for case studies on Brazil, Colombia and Ethiopia, see for instance, respectively, Ometto et al., 2013; Arias Gaviria et al., 2016; and Block and Strzepek, 2012): with our present work we contribute to and expand this literature.

Section 2 of this article summarises our methodology by concisely presenting the two models used for this study and listing the references which describe them in more detail. In section 3 we report the results from the scenario runs with our models, in terms of the evolution of Ethiopia’s energy system until 2050, respectively, the hydropower generated under specified hydrological and climatic conditions as well as assumptions on the development of water use in the domestic and irrigated agriculture sectors. In section 4 we discuss these results and draw our main conclusions based on the combined insights that derive jointly from our two models. Section 5 is dedicated to our recommendations for policy makers in Ethiopia.

2 METHODOLOGY

For our study we use two different but complementary methodologies, involving TIAM-ECN (the TIMES Integrated Assessment Model, operated at ECN) and RIBASIM (the River Basin Simulation model, developed by Deltares), respectively. TIAM-ECN is an energy system optimisation model that can be used to find the best energy mix based on a number of techno- and socio-economic conditions. RIBASIM is a water balance model that provides information on water availability based on the combination of water demand and supply functions modelled at the scale of river basins. TIAM-ECN works at the global, regional, and – more recently – national level, while RIBASIM can be implemented at the sub-catchment, basin, national or trans-boundary scale. Since TIAM-ECN and RIBASIM represent two distinct approaches of analysis, there is limited scope to fully integrate these models. There is opportunity, however, for establishing soft-linkages, implying that one can contrast their inputs, fact-check their respective results, and use the outputs from the one as inputs for the other, and vice-versa. In view of this soft-linking, we have ensured that TIAM-ECN and RIBASIM match in terms of a number of assumptions, notably in terms of geographical coverage (by singling out Ethiopia in our global TIAM-ECN model, and by using the Ethiopia's Blue Nile version of the RIBASIM model) and expected population growth (by close to a factor of two between today and the middle of the century, from a value of around 99 million people in 2015 to approximately 191 million inhabitants in 2050). The next two sections describe the main features of our two models so as to provide more insight into the characteristics of each of them.

2.1 TIAM-ECN

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 optimisation 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 minimising 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 made in 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 can hereby 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.

We ran two scenarios with TIAM-ECN: a baseline respectively stringent climate change control scenario entitled RCP2.6 (a so-called Representative Concentration Pathway with an anthropogenic radiative forcing of 2.6 W/m^2; see IPCC, 2014, for the corresponding terminology). The former is a representation of what Ethiopia's energy system may look like without the introduction of far-reaching climate policy. The latter is a scenario in which the likelihood that the global average atmospheric temperature increase stays below 2ºC is high (around 70%). As with any model, the outcome of scenario runs with TIAM-ECN is strongly determined by the values of its input parameters (see Figure 1 for a schematic diagram), which is why our scenarios should not be interpreted as forecasts, but rather as potential indications of the way in which the energy system could possibly develop in the future if all assumptions hold true. For each of the hundreds of technologies simulated in TIAM-ECN across all main energy-consuming sectors of the economy, assumptions are made on their present costs, future cost decreases, maximum penetration rates and efficiencies. Demand projections are made on the basis of assumptions with regards to e.g. population growth, welfare increases and demand-side savings and efficiencies. Other assumptions relate to e.g. fossil fuel reserves in different parts of the world, energy trade capabilities between all main regions, autonomous energy efficiency and decarbonisation processes, as well as energy or climate policies implemented prior to the reference year at which TIAM-ECN is calibrated (2010). For details on all these assumptions we refer to the publications listed above.

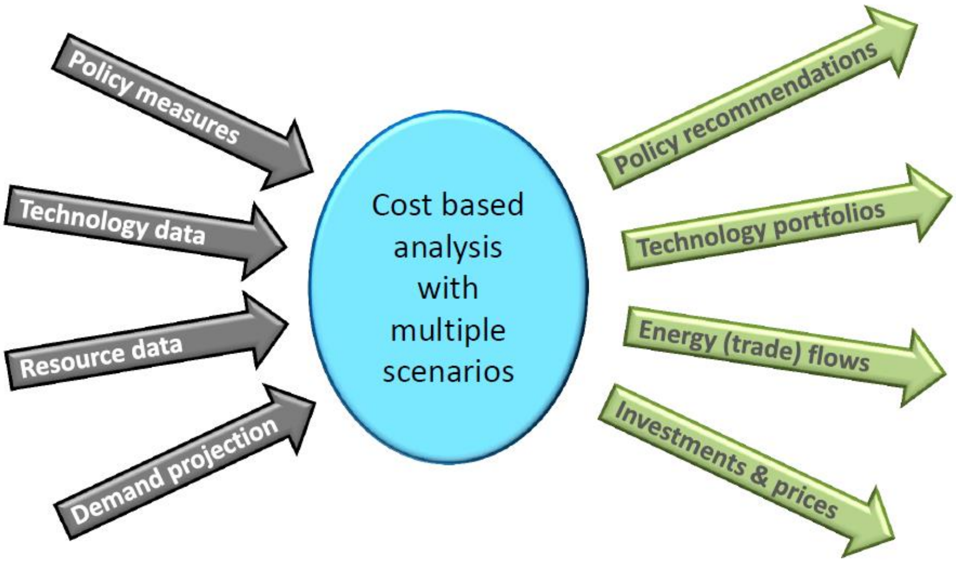

Figure 1. Stylistic representation of the main inputs and outputs of TIAM-ECN.

2.2 RIBASIM

RIBASIM is a generic modelling package for simulating the behaviour of river basins under various 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 the evaluation of various types of measures related to infrastructure and operational plus demand-side management, and enables the inspection of 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 to address 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 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 the present water basin features in Ethiopia as accurately as possible. The analysis behind the current study makes use of the existing RIBASIM schematisation 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). Here, RIBASIM is 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). By simulating just the Blue Nile part of Ethiopia, the current version of RIBASIM covers only about 32% of the entire surface of the country (see Figure 2). However, the model does fit our purposes as we calculate that about 70% of the total surface water availability is covered (for the specifics of this claim, see Boccalon, 2016).

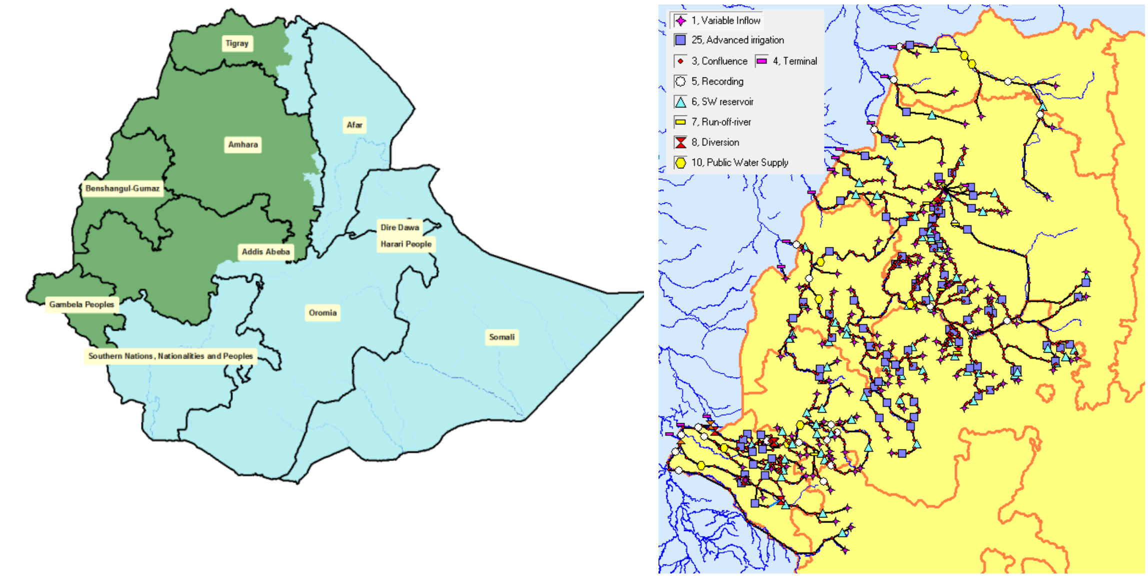

Figure 2. Blue Nile area in Ethiopia (left, in green) and RIBASIM model schematisation of surface water reservoirs and irrigation nodes in the Blue Nile river system (right).

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. Scenarios R1, R2 and R3 involve 3, 14 and 23 reservoir plants, and 2, 4 and 5 run-of-river plants, respectively, as indicated in Table 1. In total we run 5 scenarios, with R4 and R5 involving the same capacity assumptions as in R2 and R3, respectively, but under precipitation conditions that have changed with respect to historically observed patterns as a result of climate change (according to the HadGem2 RCP2.6 scenario). Table 1 summarises the five scenarios we run with RIBASIM.

Table 1. Main assumptions for the five scenarios run with the RIBASIM model.

Scenario	Year	Climate	Number of Plants	Capacity
R1: base case	2015	Historical	3 SWR + 2 RoR	890 + 540 MW
R2: expansion	2030	Historical	14 SWR + 4 RoR	14400 + 750 MW
R3: expansion	2050	Historical	23 SWR + 5 RoR	16360 + 960 MW
R4: expansion	2030	HadGem2	14 SWR + 4 RoR	14400 + 750 MW
R5: expansion	2050	HadGem2	23 SWR + 5 RoR	16360 + 960 MW

N.B. SWR: surface water reservoir plant; RoR: run-of-river plant.

Other Ethiopia-specific features reflected in the RIBASIM model include assumptions on domestic water demand and water usage for irrigation purposes representing agricultural water demand. Domestic water demand increases dramatically, both as a result of population growth (4.6%/yr in 2015-2030 and 3.5%/yr in 2030-2050 in urban areas respectively, 1.7%/yr and 0.8 %/yr in rural areas); and per capita water usage growth (20, 30 and 51 l/cap/day in 2015, 2030 and 2050 for urban people respectively, 15, 23 and 34 l/cap/day for rural people). The irrigated areas we assume for scenarios R1, R2 (R4) and R3 (R5), increase from 75,000 ha to 105,000 ha and 156,000 ha, respectively. For details on all these assumptions we refer to Boccalon (2016).

3 RESULTS

We first report the results that derive from our two models individually, in section 3.1 and 3.2 for TIAM-ECN and RIBASIM, respectively, while dedicating section 3.3 to our overall insights obtained from a merger of the outcomes from these two models.

3.1 TIAM-ECN

In Figure 3 we see that final energy use in the baseline scenario (left plot) expands by almost a factor of three in the course of four decades until 2050, as a result of both population and economic growth. The residential sector represents today almost all of this final energy use, and in 2050 it still constitutes the majority of energy use in the Ethiopian economy. As can be seen, some energy savings can be realised in this sector in the short term, notably through the replacement of current cookstoves by more efficient ones. In the longer run, however, this effect is probably overshadowed by the energy consumption associated with an increased number of modern domestic appliances used in households as incomes increase. Today, final energy use in transportation is small in comparison to that in other sectors, but by 2050 the transport sector is likely to contribute substantially, perhaps by around 25%. In the RCP2.6 scenario (right plot) we see a similar evolution of the Ethiopian energy system, but with a reduction in the overall level of final energy use of around 15% as one of the means to contribute to CO_2 emissions reduction efforts. In both plots of Figure 3 we see that industry and the commercial sector contribute only modestly to overall final energy use, while energy use in agriculture (a large contributor to GHG emissions) is negligible.

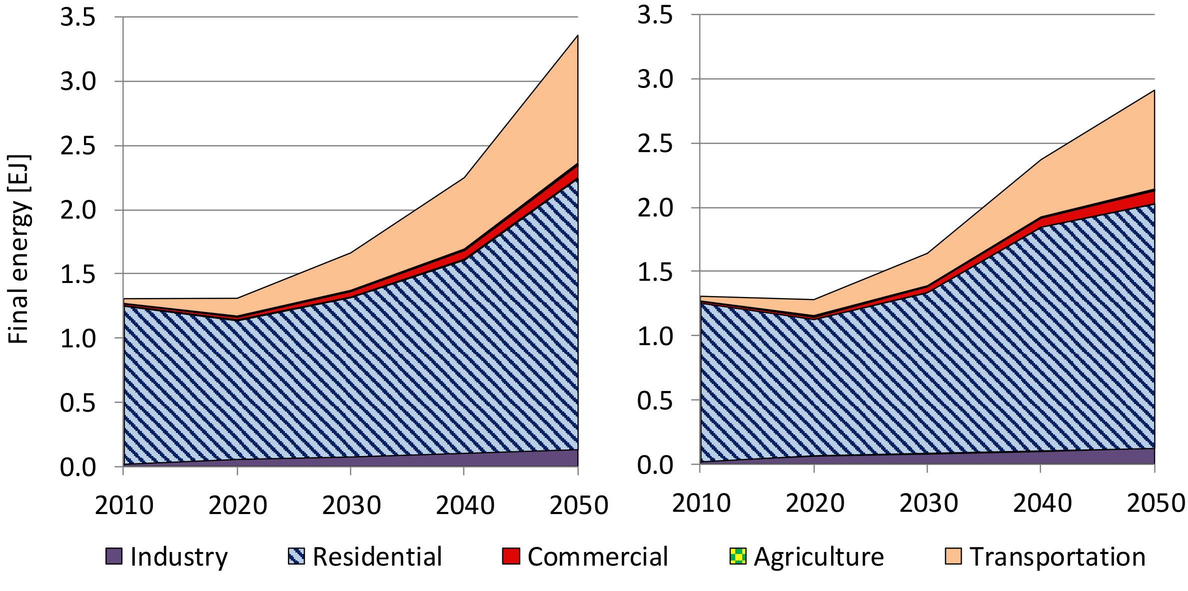

Figure 3. Final energy use by sector in Ethiopia in two scenarios: baseline (left) and RCP2.6 (right).

In Figure 4 we see the same overall final energy numbers as depicted in Figure 3, but broken down by type of fuel, rather than by sector. As one can observe in the left plot of this Figure, traditional use of biomass in the baseline is substantially curtailed in exchange for a large increase in the use of fossil fuels (coal, natural gas and oil). Electricity use also expands massively, but its share in total final energy use stays well below 20%. In the right plot of this Figure, one sees that the use of fossil fuels like oil and gas is substantially reduced, while coal is phased out altogether, given its high carbon content. Biomass re-emerges as a means to supply much of the total final energy use, but employed in modern technologies and in a non-traditional (sustainable, low-carbon) fashion. Electricity expands to a contribution of around 25%, since it provides a cost-effective way to reduce GHG emissions. Ethiopia's sizeable geothermal energy resources also start to play a significant role by the middle of the century, but mostly in their capacity to provide low-cost heat, rather than as a competitive way to generate electricity. A modest role is foreseen for the use of hydrogen as energy carrier during the forthcoming decades, but not exceeding a contribution level of a few percentage points to overall final energy use.

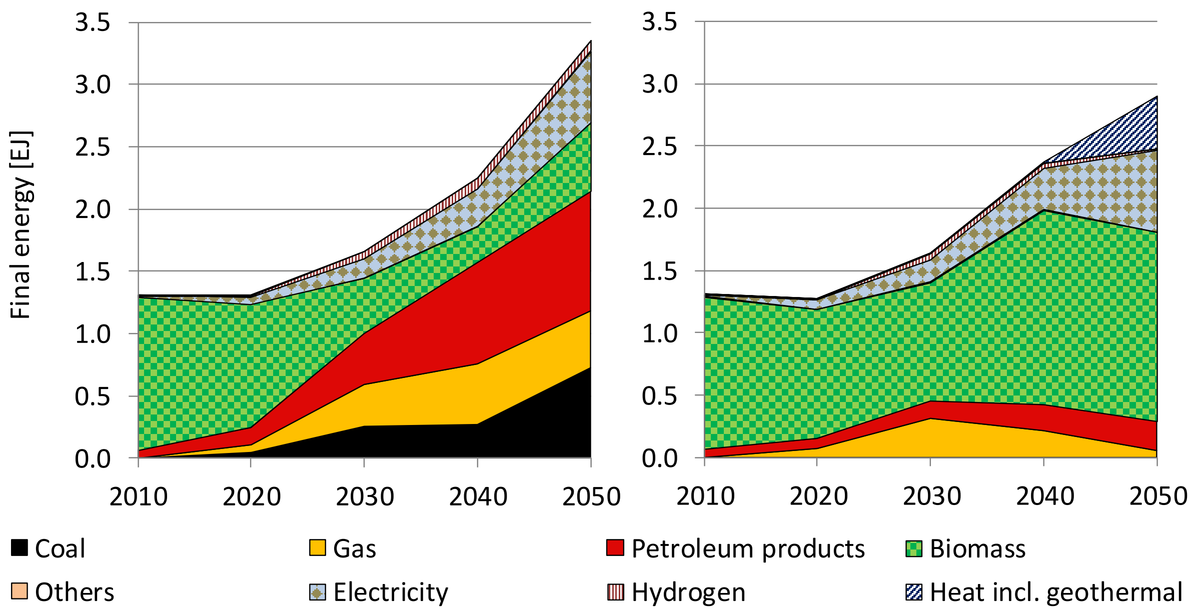

Figure 4. Final energy use by fuel in Ethiopia in two scenarios: baseline (left) and RCP2.6 (right).

Figure 5 shows that we expect the power sector in Ethiopia to massively increase, perhaps by as much as some 50-fold during the period investigated in this study until 2050. This is consistent with similar expected expansions of the power sectors in other African countries, as more people gain access to electricity supply, either through connection to the grid or by the use of mini-grids or other stand-alone systems, as well as a large increase of electricity consumption by those already using this modern energy carrier. The increase in electricity supply is even larger in the stringent climate change control scenario, in comparison to the baseline. This is consistent with our findings presented in Figure 4 where we observed that electrification is a convenient way to decarbonise energy supply.

Figure 5 also depicts the breakdown of domestic electricity generation, from which we can see that in the baseline case (left plot), hydropower could well represent around 40% of overall power production by the middle of the century. In the RCP2.6 scenario (right plot) this share could even increase to nearly 50%, in response to global GHG emissions reduction efforts that Ethiopia will need to contribute to. In other words, an order of magnitude expansion of power production by exploiting Ethiopia's vast hydrological potential appears an obvious way to sustain economic development and poverty alleviation, irrespective of whether or not the country engages in serious domestic climate change mitigation activities. From a techno-economic point of view, there is scope for such expansion, but environmental impacts, impact on rainfall due to climate change, and institutional and financial limitations may constrain it. In principle, such limitations may include water usage for other purposes (but this specific restriction appears not to be binding, as we will see in the next section).

In Figure 5 we also see that biomass could play a large role in providing electricity services, especially in the baseline scenario (left plot). In the RCP2.6 scenario (right plot), we see that options like solar power can contribute substantially too, while smaller roles are reserved for gas-based power production, wind power and imports of electricity. Hence, as we can see from Figure 5, stringent climate change control requires an enhanced use of low-carbon electricity generation, for which we think the qualifying candidate in Ethiopia would not only and particularly be hydropower, but also solar and biomass-based energy options would be included. However, here we investigate the feasibility of a large hydropower expansion further, and leave the viability of alternatives such as solar and biomass-based technologies for future inspection.

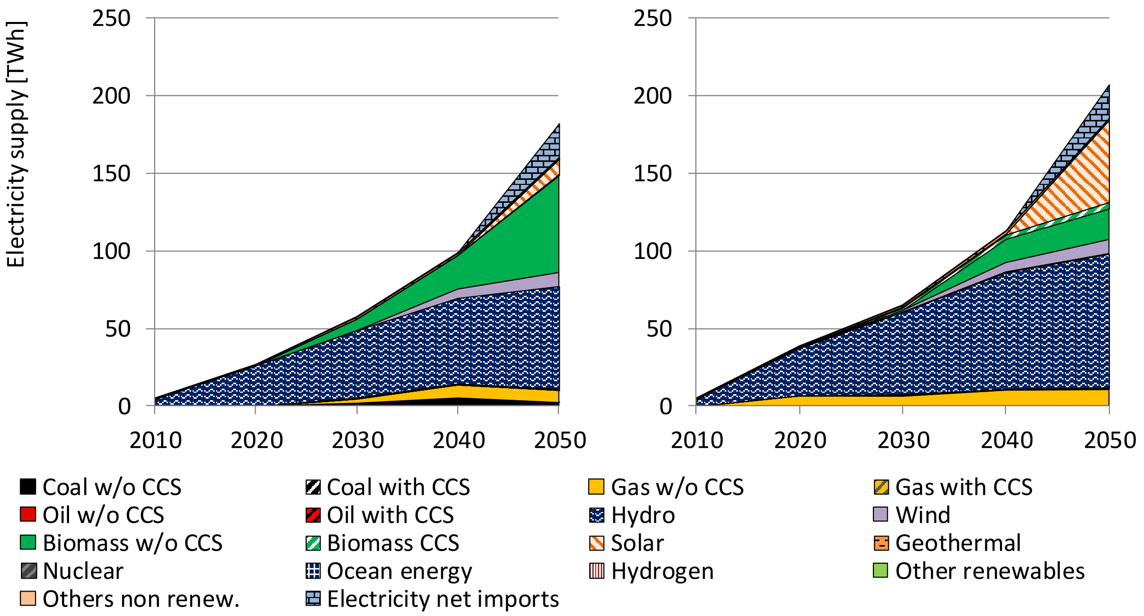

Figure 5. Electricity supply in Ethiopia by technology and resource in two scenarios: baseline (left) and RCP2.6 (right).

3.2 RIBASIM

Figure 6 shows the monthly hydropower supply in Ethiopia calculated with RIBASIM under our five scenarios. In scenario R1 we see that on average about 2900 GWh of hydropower is generated on an annual basis, with substantial variation throughout the year between September (peak production of around 360 GWh/m) and the months of the first semester (approximately 220-240 GWh/m). In scenarios R2-R5 we observe an order-of-magnitude increase in electricity generation through hydropower plants, which is in agreement with our assumption that in these scenarios the hydropower capacity is expanded approximately 10-fold with regards to scenario R1. A striking difference between R1 and R2-R5 is that the inter-month variability increases substantially: whereas in R1 the peak-month yields around 50% more hydro-electricity than in any of the minimum-producing months, in scenarios R2-R5 this difference is in some cases as much as 100%.

The increase in hydropower production between R1 and R2 is mainly driven by 4 of the 11 additional hydropower plant projects realised between today and 2030: the Mendaia, Grand Renaissance, Karadobi and Beko Abo surface water reservoirs, accounting for 81% (29%, 25%, 17% and 10%, respectively) of all hydroelectricity generated in 2030. The additional 9 hydropower dams assumed to be built between 2030 and 2050 add approximately 2,000 MW of installed capacity, which normally would add around 4,000 GWh of hydro-electricity production to the entire Blue Nile basin in Ethiopia on an annual basis, which is around 400 GWh on a monthly basis. The explanation for the fact that this effect cannot be clearly seen in Figure 6 by comparing scenarios R2 and R3 or, alternatively, scenarios R4 and R5, is that some of the additional capacity operates at a low load factor in reality. The seasonal variation of power production with hydro-electrical dams is a feature that EEPCO will need to account for in its reliability strategy, like the intermittency of other forms of renewable energy such as solar and wind power also needs to be duly taken into consideration by utilities and operators of plants and transmission lines.

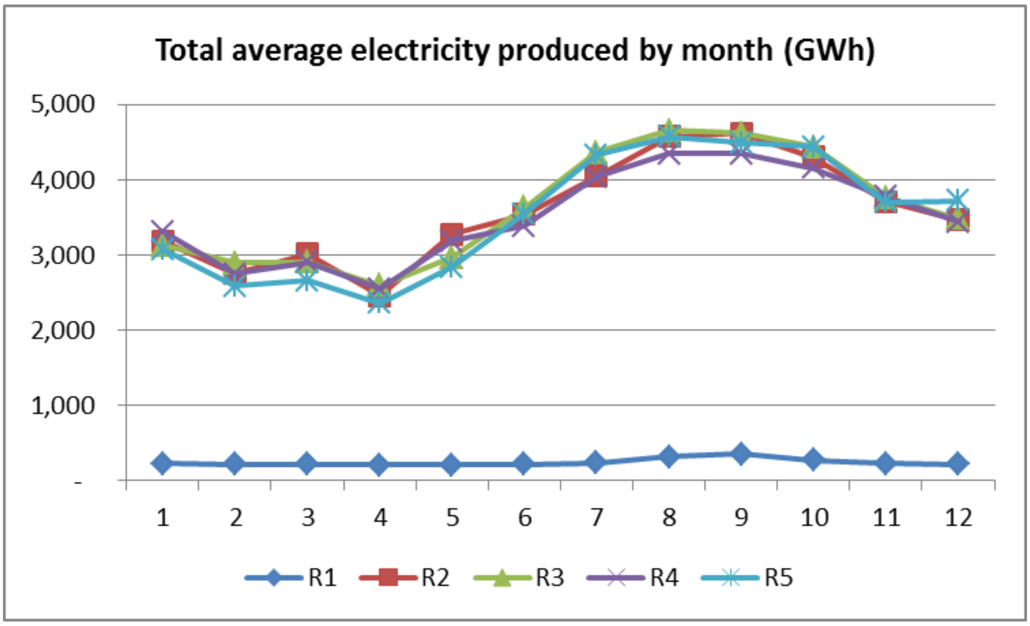

Figure 6. Monthly hydropower supply from surface water reservoirs in Ethiopia's Blue Nile river basin under our five scenarios.

Figure 7 depicts the annual average hydropower supply from surface water reservoirs in Ethiopia in 2030 (R2 and R4) and 2050 (R3 and R5) under the no-climate and climate change scenarios respectively. The y-axis is cut off at 41,500 GWh, so that relative differences between scenarios can be seen more clearly than they appear in the Figure. As one can see, in 2030 climate-change induced modifications in precipitation levels lead to a decrease of around 800 GWh of hydro-electricity generation, while in 2050 the corresponding reduction amounts to close to 1,200 GWh. As can be concluded from a comparison between scenarios R2 and R5 in Figure 7, the additional hydropower capacity installed between 2030 and 2050 cannot compensate for the loss in hydro-electricity generation in those years as a result of climate-change induced losses of rainfall.

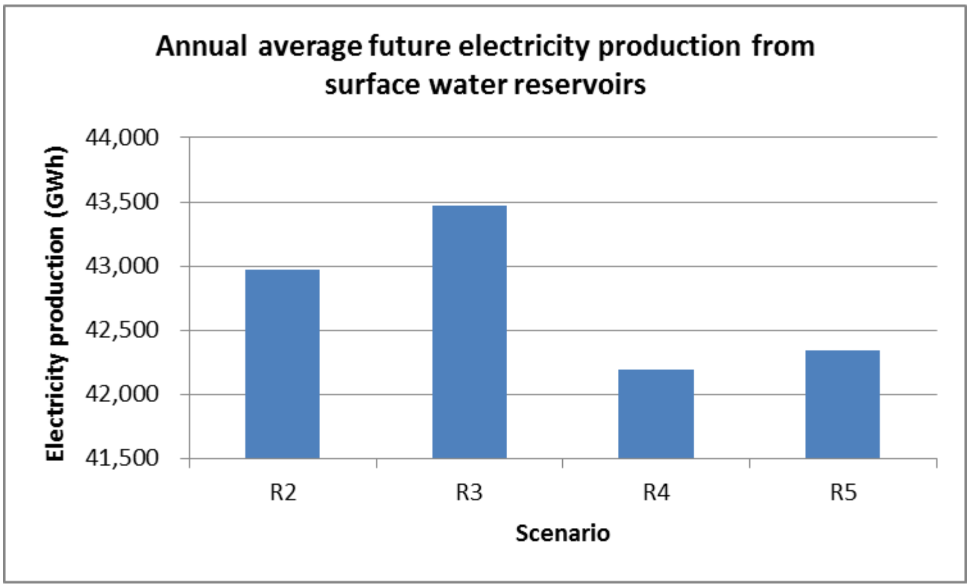

Figure 7. Annual average hydropower supply from surface water reservoirs in Ethiopia's Blue Nile river basin under scenarios R2, R3, R4 and R5.

Figure 8 shows a comparison of the timing of precipitation, on the one hand, and water demand from hydropower production, irrigated agriculture and domestic usage (drinking/cooking, cleaning and sanitation), on the other hand, in scenario R2. As one can see in this Figure, water demand for irrigation purposes drops to zero for several months from May onwards, which is when most of the precipitation takes place. During the same period hydropower production ramps up by almost a factor of two: this rapid increase in water usage in the power sector does not inflict on agriculture since the latter is in no need for water other than directly from rainfall during that period. During the dry months (January-April), irrigation demand is at its highest level, but water needs for power production are at its lowest level, so there is no conflict of interests theoretically during those months either. Water demand for domestic purposes is relatively stable during the year but somewhat increases during the wet season. The strong increase in rainfall in that period can largely compensate for the small temporary increase in domestic water demand during those months. One also observes from Figure 8 that the peak in hydropower production follows the peak in precipitation with a delay of a couple of months, after which surface water reservoirs have been replenished.

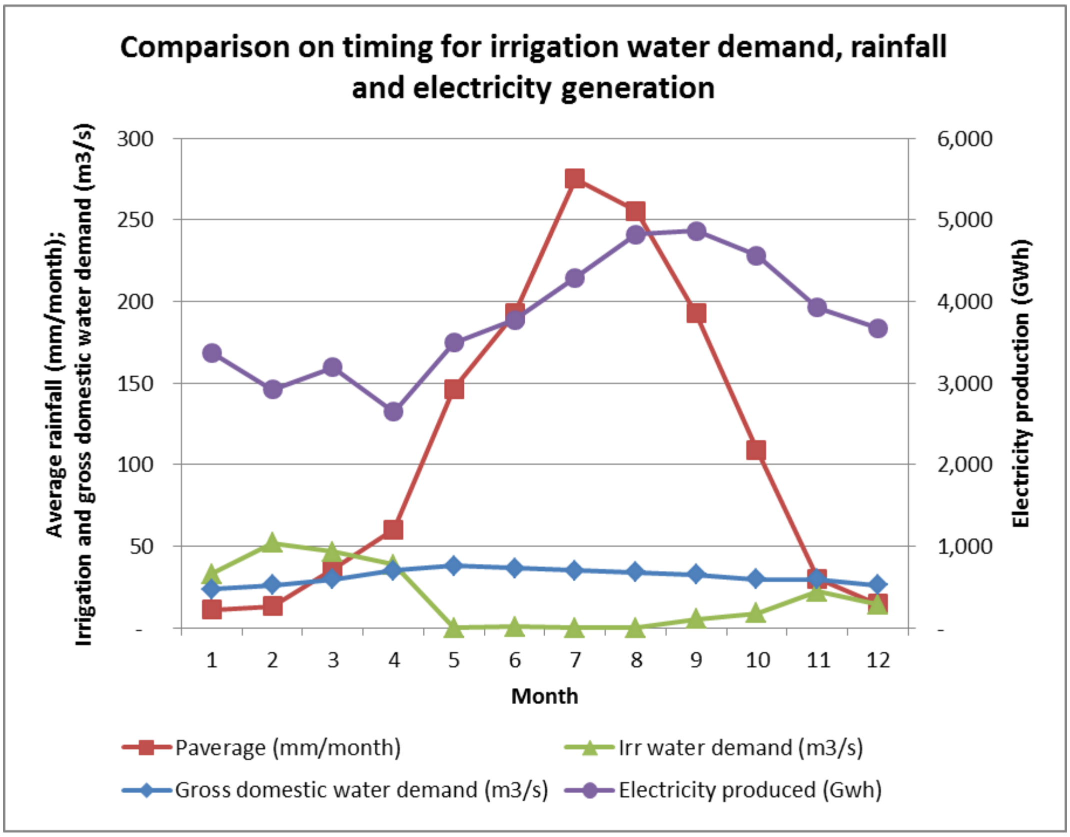

Figure 8. Comparison of the timing between precipitation and water use for respectively power production, irrigation and domestic purposes in scenario R2.

3.3 Combined insights

In Table 2 we summarise, as well as contrast, the main results for annual hydropower generation in 2050 that derive from TIAM-ECN and RIBASIM. For both models the values reported in this Table include our findings for reservoir-based and run-of-river electricity generation. In the case of RIBASIM the outcome for run-of-river hydropower production, of approximately 2,500 GWh, varies little between 2030 and 2050, and is little influenced by climate-change induced precipitation changes. For reservoir-based power production, however, the difference as a result of climate change can amount to a significant drop, as can be seen in Table 2. We distinguish three different climate futures: one in which negligible climate change occurs (precipitation levels until 2050 mimic the average historical values between 1960 and 2000), one in which moderate climate change takes place with local impacts in Ethiopia in terms of e.g. altered precipitation levels (an RCP2.6 emissions scenario is followed, in which the climate stabilises likely below a 2°C global temperature increase), and one in which enhanced climate change materialises (a baseline emissions pathway is followed that leads to a radiative forcing of 7.0 W/m^2 in 2100). For RIBASIM the first two climate futures are characterised by scenarios R3 and R5 respectively, while for TIAM-ECN the last two climate futures correspond to respectively the RCP2.6 and baseline scenarios. Column 3 of Table 2 lists the annual average hydro-electricity generation levels (in GWh) in 2050 for the first two climate futures calculated with RIBASIM. Since RIBASIM only covers the Blue Nile basin and thereby only 63% of the expected hydropower capacity in 2050, in column 4 these numbers are 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 numbers that TIAM-ECN projects for hydro-electric energy production by the middle of the century, for the last two climate futures.

Table 2. 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

Our first observation from Table 2 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 easily be explained; however, by the fact that RIBASIM does not include any plants that are not yet in some stage of planning, while ample opportunity exists for more hydropower projects. In other words, in order to achieve the large amount of hydro-electricity production that TAM-ECN foresees, a capacity needs to be installed by 2050 that goes well beyond what is foreseen in current plans. Hence more hydropower plants need to be built than the 28 surface water reservoir plants and 5 run-of-river plants that are currently operating, being built or planned for construction until 2050. The explanation for the large amount of hydropower production projected with TIAM-ECN is that it is the level deemed required in order for Ethiopia to contribute its share in global climate change control.

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 5 as determined with TIAM-ECN derive from installed capacities of around 15 and 20 GW in 2050 for our two scenarios, baseline versus RCP2.6, respectively. As reported in Table 1, 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 reflect 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 (Bartle, 2002; Block and Strzepek, 2012). 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.

4 DISCUSSION AND CONCLUSIONS

Through our two different approaches we find a high projection for future hydropower generation in Ethiopia: between 71 and 87 TWh/yr by 2050 in a stringent climate change control scenario in which Ethiopia contributes substantially to global efforts to reach the 2°C target fixed in the Paris Agreement (COP-21, 2015). This elevated level is obtained despite domestic and irrigated agriculture water demand expansions, and irrespective of possible hydrological effects from climate change in terms of decreased average precipitation levels at the national scale. This amount of hydropower production falls well within the estimated domestic potential in capacity terms of 45 GW, which theoretically could yield an electricity generation level between 100,000 and 200,000 GWh/yr.

We also point out, however, that Ethiopian authorities should take due account of climate change effects at the local level in terms of changes in rainfall during some months, which we think should be researched in greater detail. Stakeholders should also be consulted….environmental impact assessment carried out etc…. Substantial effort was put into feeding RIBASIM with inputs with regards to the local effects of climate change in Ethiopia. RIBASIM uses precipitation data from around 200 weather stations in the country, on the basis of which it determines the hydrological features and water availabilities at the sub-zone, zone and basin level. For changes in the rainfall patterns as a result of climate change, the effects at 6 of these weather stations (one for each of the distinct weather types in the 6 zones of our basin) were inspected in detail on a monthly basis and were used to represent climate variations at all of the 200 locations throughout the Blue Nile river basin. Under our HadGem2 RCP2.6 scenario we observed changes in precipitation levels of almost any value between -70% and 260% depending on the weather station and month under consideration. These translated in average changes between -14% and 27% in 2050, depending on the weather zone considered, and were introduced as such in RIBASIM. One of the ways in which our research could be improved would be to use the variations at all 200 weather stations represented in RIBASIM. Given the size of the efforts involved in such research, we reserve them for a future study. For further details on how we accounted for highly detailed information on precipitation levels in RIBASIM, see Boccalon (2016) we referred to.

The outcomes for RIBASIM and TIAM-ECN reported in Table 2 are not complete, hence some cells are left blank. The enhanced climate change (baseline) scenario run with TIAM-ECN implies by 2100 an anthropogenic radiative forcing of 7 W/m^2, which is a scenario we did not run with RIBASIM. We could contemplate to do so in the future, as the implications of such a scenario at the local level could already be significant by 2050. To date, however, we cannot draw any conclusions about the possible changes in precipitation levels in Ethiopia as a result of such an enhanced climate change scenario. The HadGem2 scenario run with RIBASIM, on the other hand, prescribes in great detail what these domestic changes as a result of moderate climate change could be in Ethiopia at the level of individual communities. In an expanded analysis that we could undertake in the future, we could also investigate other HadGem2 scenarios, such as an RCP3.5 or RCP4.5, to mention just a few. For the negligible climate change scenario that we projected for the future with RIBASIM, the same precipitation patterns were taken as observed historically between 1960 and 2000, which should yield a reasonable reflection of negligible climate change conditions until 2050. For TIAM-ECN, however, the closest we can get to a negligible climate change world is probably the RCP2.6 scenario, since more ambitious scenarios that we investigated resulted in model infeasibilities. Hence a 70% probability of staying below 2°C – which we here call moderate climate change – is as close as we can get with TIAM-ECN to RIBASIM's R3 scenario.

Our work has similarities with research undertaken on this topic by Block and Strzepek (2012), since their study, like ours, deals with the prospects for hydropower in Ethiopia, and likewise covers a time horizon that extends until 2050. Apart from some overlap, however, our respective studies are largely complementary. Block and Strzepek (2012) assess planned hydropower development under various future climates, and calculate the costs associated with compensating for hydropower generation losses under climate change conditions. We, on the other hand, 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 local climate change effects as well as expected increases in water demand from domestic and agricultural purposes.

5 POLICY IMPLICATIONS

Our main recommendation is to continue on the ambitious development trajectory for hydropower in Ethiopia as currently planned by national authorities. This development is needed to meet targets for economic growth and welfare increase without correspondingly increasing GHG emissions. From our analysis it seems unlikely that possible future climate change trends will pervasively and negatively impact hydropower production on a national level, even while at the local level individual hydropower plants may be subject to increased precipitation variability emanating from climate change. Since there are multiple questions left unanswered in our analysis, such as in terms of the local impacts of climate change during short intervals (typically at the scale of months) for some hydropower plants, we recommend that multidisciplinary research continues, such as our joint two-model-based approach. Such research can yield insights that cannot be achieved from one disciplinary perspective, or through one type of model only.

The robustness of the numbers obtained independently through our two distinct modelling approaches implies that our findings based on cost-minimisation of Ethiopia's national energy system (TIAM-ECN) match in principle the limits imposed by domestic water demand and use by irrigated agriculture as well as variations emanating from climate change on a national average level (RIBASIM). They match even while the latter model would need to simulate more hydropower projects than currently foreseen in order to reach the upper limit of hydropower capacity calculated with the former. In addition to our recommendation that Ethiopia pursue its current ambitious hydropower development plans, we also suggest that Ethiopia's energy planning authorities take due account of climate change effects in terms of possible changes in rainfall at the local level, since for some months these could lead to substantial reductions in power production levels at some hydro-electric plants. We think that local climate change impacts should be researched in greater detail than the present study has allowed. Since at certain locations hydroelectricity production may occasionally be curtailed by a decrease in precipitation, these effects should be accounted for in national low-emission development strategies (LEDS) based on hydropower, and require further detailed studies.

The large expansion of the use of hydropower as described in this paper necessitates significant 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-change induced water availability effects. 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 2040-2050 under varying assumptions with regards to future climate change developments in Ethiopia. This increases the credibility of our analysis, and reinforces the recommendation for the Ethiopian government to continue its ambition to massively invest in domestic hydropower development through dedicated national policy schemes.

Another message to the policy making scene is that Ethiopia's government, in view of its intention to invest heavily in hydropower, should be aware of some of the possible environmental effects of such a massive deployment and should takes stock of the potential consequences the large-scale use of hydropower could have on water users downstream, notably in South Sudan, Sudan and Egypt. Ethiopia should probably also not become over-reliant on hydropower, since arguments other than climate change (such as major accidents or dam breaches) suggest to keep the overall energy system diversified, so as to hedge against situations in which for one reason or another an energy option suddenly is taken out of the portfolio. Hence it would be wise for Ethiopia to stay well below the limits at which projected hydroelectricity generation can be securely provided. To the policy research community we would like to convey that our models can be refined and expanded, for example to verify whether our conclusions still hold under conditions in which biomass also becomes an important part of Ethiopia's energy system. The water requirements thereof will then need to be accounted for in our study. Ethiopia intends to heavily invest in afforestation in order to reach its NDC ambitions. How does the water demand associated with afforestation change the findings reported in this paper? Are our projections for domestic water demand and irrigated agriculture increases accurate, and are there more topics that we should account for if we want to further energy-water-food nexus research? These are the sorts of questions we would like to address in follow-up work.

References

Arias Gaviria, J., B. van der Zwaan, T. Kober, S. Arango Aramburo, 2016, "Prospects for Small Hydropower in Colombia: an inspection of Learning-by-doing and Economies-of-scale", working paper submitted for review.

Bartle, A., 2002, "Hydropower potential and development activities", *Energy Policy*, 30, 14,1231-1239.

Block, P., K. Strzepek, 2012, "Power Ahead: Meeting Ethiopia's Energy Needs Under a Changing Climate", Working paper, Columbia University, New York USA.

Boccalon, A., 2016, "Report on the Water-Energy-Food Nexus Case Study in the Blue Nile of Ethiopia", internal report, Deltares.

Calvin, K., L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, E. Kriegler, G. Luderer, P.R. Shukla, 2012, "The role of Asia in mitigating climate change: Results from the Asia modeling exercise", *Energy Economics*, 34, Supplement 3:S251-S260.

Collins, W.J., N. Bellouin, M. Doutriaux-Boucher, N. Gedney, T. Hinton, C. D. Jones, S. Liddicoat, G. Martin, F. O'Connor, J. Rae, C. Senior, I. Totterdell, S. Woodward, T. Reichler, J. Kim, 2008, "Evaluation of the HadGEM2 model", Met Office Hadley Centre Technical Note no. HCTN 74, available from www.metoffice.gov.uk/publications/HCTN/index.html.

COP-21, 2015, Paris Agreement, United Nations Framework Convention on Climate Change, Conference of the Parties 21, Paris, France.

Deltares, 2016, "River Basin Planning and Management", brochure RIBASIM software, Delft, The Netherlands.

GEA, 2012, *Global Energy Assessment*, IIASA (Laxenburg, Austria), Cambridge University Press, Cambridge, UK.

Jones, C.D. *et al.*, 2011, "The HadGEM2-ES implementation of CMIP5 centennial simulations", *Geoscientific Model Development*, 4, 543–570.

IEA-ETP, 2016, International Energy Agency (IEA), OECD, *Energy Technology Perspectives (ETP)*, Paris, France.

IEA-WEO, 2014, International Energy Agency (IEA), OECD, *World Energy Outlook (WEO)*, Special Report, Africa Energy Outlook, Paris, France.

INDC-Ethiopia, 2015, Intended Nationally Determined Contribution (INDC) of the Federal Democratic Republic of Ethiopia.

IPCC, 2011, *Special Report on Renewable Energy Sources and Climate Change Mitigation*, Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC, 2014, *Climate Change Mitigation*, Fifth Assessment Report (AR5), Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press.

IRENA, 2015, International Renewable Energy Agency, "Renewable Energy in the Water, Energy & Food Nexus", Bonn / Abu Dhabi.

Keppo, I., B.C.C. van der Zwaan, 2012, "The Impact of Uncertainty in Climate Targets and CO_2 Storage Availability on Long-Term Emissions Abatement", *Environmental Modeling and Assessment*, 17, 1/2, 177-191.

Kober, T., B.C.C. van der Zwaan, H. Rösler, 2014, "Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2˚C Climate Change Control Target", *Climate Change Economics*, 5, 1, 1440001, 1-32.

Loulou, R. and M. Labriet, 2008, "ETSAP-TIAM: the TIMES integrated assessment model, Part I: Model structure", *Computational Management Science*, 5, 1-2, 7-40.

Loulou, R, 2008, "ETSAP-TIAM: the TIMES integrated assessment model, Part II: mathematical formulation", *Computational Management Science*, 5, 1-2, 41-66.

Lucas, P.L., J. Nielsen, K. Calvin, D. McCollum, G. Marangoni, J. Strefler, B. van der Zwaan, D.P. van Vuuren, 2015, "Future energy system challenges for Africa: insights from Integrated Assessment Models", *Energy Policy*, 86, 705-717.

MWE, 2011, Ministry of Water and Energy, Energy Study and Development, Follow-up Directorate, "Power Generation Projects Open for Private Sector Participation", Ethiopia.

J.P. Ometto, A.C.P. Cimbleris, M. a. dos Santos, L.P. Rosa, D. Abe, J.G. Tundisi, et al., 2013, Carbon emission as a function of energy generation in hydroelectric reservoirs in Brazilian dry tropical biome, *Energy Policy*, 58, 109–116.

Rösler, H., B.C.C. van der Zwaan, I.J. Keppo and J.J.C. Bruggink, 2014, "Electricity versus Hydrogen for Passenger Cars under Stringent Climate Change Control", *Sustainable Energy Technologies and Assessments*, 5, 106-118.

Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H. and E. Peltola, 2008, "Global energy and emissions scenarios for effective climate change mitigation – Deterministic and stochastic scenarios with the TIAM model", *International Journal of Greenhouse Gas Control*, 2, 2, 274-285.

UN, 2012, "Sustainable Energy for All: A Framework for Action", United Nations, The Secretary-General's High-level Group on Sustainable Energy for All, New York.

van der Krogt, W.N.M., 2016, River Basin Simulation Model, RIBASIM Version 7.00, model description & short presentation, Delft, The Netherlands.

van der Laan, A., 2015, "Leapfrogging in the African Power Sector: The Effect of Mitigation Policies on Regional African Power Sector Development", Master Thesis Energy Science, Utrecht University/ECN, 2015.

van der Zwaan, B.C.C., I.J. Keppo, F. Johnsson, 2013a, "How to Decarbonize the Transport Sector?", *Energy Policy*, 61, 562-573.

van der Zwaan, B.C.C., H. Rösler, T. Kober, T. Aboumahboub, K.V. Calvin, D.E.H.J. Gernaat, G. Marangoni, D.L. McCollum, 2013b, "A Cross-Model Comparison of Global Long-Term Technology Diffusion under a 2˚C Climate Change Control Target", *Climate Change Economics*, 4, 4, 1-24.

van der Zwaan, B.C.C., K. Calvin, L. Clarke (Guest Editors), 2016a, “Climate Mitigation in Latin America: implications for energy and land use”, Preface to the Special Issue on the findings of the CLIMACAP-LAMP project, *Energy Economics*, 56, 495-498.

van der Zwaan, B.C.C., T. Kober, S. Calderon, L. Clarke, K. Daenzer, A. Kitous, M. Labriet, A.F.P. Lucena, C. Octaviano, N. Di Sbroiavacca, 2016b, “Energy Technology Roll-Out for Climate Change Mitigation: A Multi-Model Study for Latin America”, *Energy Economics*, 56, 526-542.