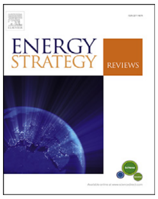
Energy Strategy Reviews 19 (2018) 19–30

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.ees.elsevier.com/esr



Prospects for hydropower in Ethiopia: An energy-water nexus analysis

Bob van der Zwaan [a, b, c, *], Agnese Boccalon [d], Francesco Dalla Longa [a]

[a] *Energy Research Centre of the Netherlands (ECN), Policy Studies, Amsterdam, The Netherlands*
[b] *Johns Hopkins University, School of Advanced International Studies (SAIS), Bologna, Italy*
[c] *University of Amsterdam, Faculty of Science (HIMS), Amsterdam, The Netherlands*
[d] *Deltares, Delft, The Netherlands*

ARTICLE INFO

Article history:
Received 24 May 2017
Received in revised form
1 November 2017
Accepted 2 November 2017
Available online 21 November 2017

Keywords:
Climate change mitigation
Hydropower
Impacts
Ethiopia
Energy-water nexus

ABSTRACT

In this article we investigate the prospects for large-scale hydropower deployment in Ethiopia. With two distinct modelling approaches we find high projections for future hydropower generation: 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 of the Paris Agreement. This elevated level is obtained despite domestic water use and irrigated agriculture water demand expansions, and irrespective of hydrological effects from climate change in terms of a drop in average precipitation nationwide. This amount of hydro-electricity production matches the expected national hydropower potential. Yet, we encourage authorities to take due account of the large impact that climate change may have on rainfall during particular months or years at individual water reservoirs, which we think should be researched in greater detail. Our combined energy cost-minimisation and hydrological balance analysis shows that our models can be jointly used for the assessment of hydropower as climate change mitigation option, and can assist in the design of policies that integrate the energy and water sectors. Our case study did not yield direct reasons for the Ethiopian government to swiftly stop pursuing its current ambitious national hydropower development plan, but we encourage it to adequately internalise an extensive range of factors — including environmental, geopolitical and social — that may induce it to take a different course.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has published voluminous reports on the large-scale global deployment of renewable forms of energy to achieve deep cuts in greenhouse gas (GHG) emissions, with the aim of mitigating climate change [1,2]. 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 atmospheric temperature increase fixed in the Paris Agreement [3]: for recent studies on Asia, Africa and Latin America, see e.g., respectively, [4,5]; and [6]. Africa occupies a special place among these developing regions, since it is exceptionally rich in energy resources, yet at the same time currently poor in energy supply, notably in Sub-Saharan Africa [7]. 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*" [7]. This article builds on the growing literature that attempts to answer the question how modern forms of energy supply that contribute to mitigating climate change, can meet a rapidly increasing energy demand in Africa. We add to this literature by performing a case study dedicated to the implementation of low-emission development strategies (LEDS) in Africa's second most populous country, Ethiopia.

Under the Paris Agreement all countries committed to realizing 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 of 400 $MtCO_2e$ in 2030 by 64%, implying a decrease of 255 $MtCO_2e$ down to 145 $MtCO_2e$ [8]. Of this total GHG emissions reduction figure, 130 $MtCO_2e$ is realized in forestry and 90 $MtCO_2e$ in agriculture, with the remaining 35 $MtCO_2e$ materialized through a combination of GHG abatement efforts in transportation, industry and buildings. The power sector

---

* Corresponding author. Energy Research Centre of the Netherlands (ECN), Policy Studies, Amsterdam, The Netherlands.
E-mail address: vanderzwaan@ecn.nl (B. van der Zwaan).

https://doi.org/10.1016/j.esr.2017.11.001

is projected to remain at its current emission level of 5 $MtCO_2e$, even while this sector is expected to grow substantially in order to satisfy increasing demand of, and expand access to, electricity.

In Ethiopia low-carbon energy options like wind and geothermal power possess large resource potentials, and it has long been recognised that the economic potential for hydropower is massive. Ethiopia has ambitious plans for bolstering economic growth and aims at fulfilling 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 GHGs, particularly CO_2. It is estimated that Ethiopia is endowed with about 140,000 Mm^3/yr of freshwater, 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. 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 [9].

Today about 2 GW of hydropower capacity is in operation in Ethiopia, and construction is underway to multiply this level fivefold 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, describes how it intends to greatly expand its hydropower capacity over the next few decades [9]. Our purpose in this article is to shed light on the desirability and feasibility of such a large role for hydropower in Ethiopia's electricity generation system. We do so in a time frame until 2050 by employing a combination of two models, TIAM-ECN and RIBASIM. This allows for inspecting two distinct sectoral perspectives, that enable, respectively, performing detailed energy systems analysis through a cost-minimisation procedure, and undertaking a river basin water balance assessment under varying conditions of surface water supply, domestic water usage and water demand from agriculture.

In this paper we first investigate the large-scale use of hydropower in Ethiopia from a cost-optimality perspective. We next analyse it from a hydrological point of view for the Ethiopian part of the Blue Nile river system, and inspect the multiple effects of population growth and the future possible vulnerability and variability of hydro-electricity generation due to likely impacts of climate change. On the basis of the domestic geographical distribution of water resources and the foreseen plans for hydropower development, we extrapolate our results for the Blue Nile to the national level. With our research we connect to studies with a global focus on the challenges of renewable energy deployment (such as [10,11]). We contribute to work that analysts undertake to address the question how to provide “sustainable energy for all” in Africa [12]. By focusing on the use of hydropower and its ramifications in Ethiopia, we also make a deep-dive into the water-energy-food nexus discussion (see e.g. [13]). Given the magnitude of required GHG emission cuts world-wide, the contribution from hydropower in national mitigation efforts is drawing renewed interest, particularly in developing countries (for case studies on e.g. Brazil, Colombia and Ethiopia, see for instance, respectively, [14–16]): with our present work we intend to expand this scientific literature.

Section 2 of this article summarizes our methodology by concisely presenting the two models used for our study (and listing the references in which more model details can be found). In section 3 we report the results from our scenario runs for the evolution of Ethiopia's energy system until 2050, and for the level of hydropower generated under specified hydrological and climatic conditions and assumptions on the development of water usage in agriculture and for domestic purposes. In section 4 we discuss these results, draw our main conclusions based jointly on the insights that derive from the two models, and put our findings in a broader perspective. Section 5 is dedicated to our recommendations for analysts and 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 optimization 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 main 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 (from a value of around 99 million people in 2015 with a gradually declining growth rate to approximately 191 million inhabitants in 2050; see [17]). In the next two sections a description is provided of 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 [18] and Loulou [19]. TIAM is a linear optimization model simulating the development of the global energy economy from resource extraction to final energy use over a period of over 100 years. Its regional disaggregation separates the world in a number of distinct geographical areas, 20 until recently for TIAM-ECN. The objective function of TIAM-ECN consists of the total discounted aggregated energy system costs calculated over the full time horizon and summed across all regions. Running scenarios with TIAM-ECN involves minimizing this objective function.

The main cost components included in the objective function are investment costs, fuel costs and fixed plus variable operation and maintenance costs. Smaller cost components such as decommissioning and infrastructure costs are also included, albeit in an approximate respectively stylistic way. Since TIAM-ECN is based on a partial equilibrium approach with demands for energy services responding to changes in their respective prices through end-use price elasticities, savings of energy demand and corresponding cost variations are accounted for in the objective function as well. The database associated with TIAM-ECN includes hundreds of technologies for a broad set of different sectors: for a general description of the reference energy system of TIAM-ECN see also Syri et al. [20]. 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 [21,22]), the power sector [23], and burden-sharing among countries for global climate change control [24]. 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: [25,26].

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 [27]). Replacing the original representation of Africa as one single region by one in which the African continent is broken down in 17 distinct entities allows us not only to more accurately simulate developments that relate to the region as a whole (and its interactions with the rest of the world), but also to inspect in greater detail the energy systems of individual countries and sub-regions in Africa. We hereby can connect closer to the economic and political realities of different geographical areas in Africa, which vary broadly from one country to the other. We are thus also able to better represent and analyse their specific technical and resource potentials, which diverge substantially across distinct sub-regions of the African continent, in terms of the availability of both traditional fossil fuels and renewable energy options. This article is dedicated to Ethiopia, and for its purposes we have ensured that Ethiopia's current and likely near-term energy system is represented in its entirety, including all main energy-consuming sectors and energy-providing technologies, as realistically as possible. This allows for using TIAM-ECN for long-term projections until 2050.

We run 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 [2], 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 is high (around 70%) that the global average atmospheric temperature increase stays below 2 °C. As with any model, the outcome of scenario runs with TIAM-ECN is strongly determined by the values of its input parameters (see Fig. 1 for a schematic diagram), which is why our scenarios should not be interpreted as forecasts, but rather as projections of the way in which the energy system could possibly develop in the future. 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 our assumptions with regards to 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. For details on all these assumptions we refer to the publications listed in this sub-section.

2.2. RIBASIM

RIBASIM is a generic modelling package for simulating the behavior of river basins under various hydrological conditions (for detailed descriptions of the model, see e.g. [28,29]). RIBASIM is a comprehensive and flexible tool that links hydrological water inputs at various locations in a specified region with water-users in the basin. It allows for evaluating various types of measures related to infrastructure and operational plus demand-side management, and enables inspecting a series of variables such as water quantity, water quality and flow composition. The model can also generate water flow patterns that may yield a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. The RIBASIM software package includes a range of DELFT Decision Support Systems Tools, and is designed for addressing a series of question types that relate to the water sector and water users in particular.

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

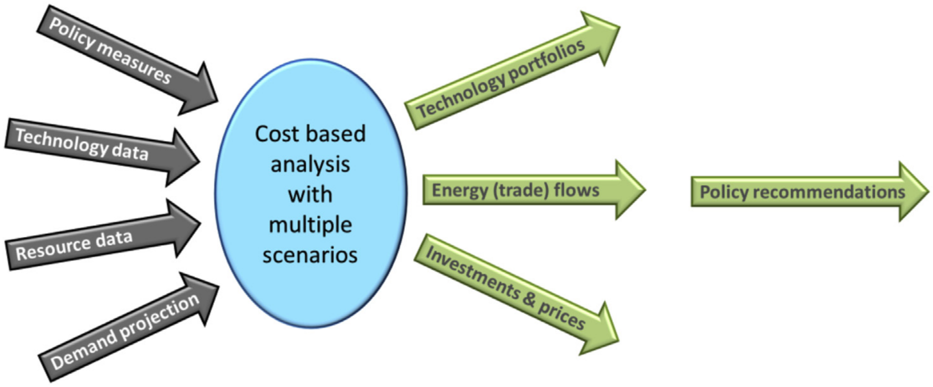


Fig. 1. Stylistic representation of the main TIAM-ECN inputs and outputs and how policy recommendations can be formulated on the basis of the latter.

composition; what are the agricultural production yields and costs of the implementation of such measures?). More generically, RIBASIM allows for performing essentially any type of analysis that requires the water balance of a river basin to be calculated, by taking into account the use by and drainage from agriculture, the use by and discharges from industry, domestic water demand for drinking, cleaning and sanitation purposes, and downstream re-use of water. The resulting water balance can provide the basic information needed to determine the available quantity and quality of water, as well as detailed results usable for water resources planning and water policy design.

RIBASIM has recently been used to perform an analysis for Ethiopia. It has been updated for the purpose of the present study to reflect as accurately as possible the main water sector features in Ethiopia. The analysis behind the current study makes use of the existing RIBASIM schematization developed under the ENWSM (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 [30,31]), downscaled at the sub-regional level to generate both climate and hydrological input for the model (for a detailed description, see [32]). In this study the ENTRO version of RIBASIM is used only for the section of the Nile river basin belonging to Ethiopia. RIBASIM results from this study can therefore not be used to inspect the 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. While we recognize the importance of such potential impacts, the focus of our study was to investigate the prospects for large-scale hydropower deployment in Ethiopia using a combined energy-water sector approach. Although by just simulating the Blue Nile part of Ethiopia the current version of RIBASIM only covers about 32% of the entire surface of the country (see Fig. 2a and b), we estimate that still about 70% of the total surface water availability in the country is covered, so that the model fits our purposes (for the specifics of this claim, see [32]). We adopted hydropower turbine efficiencies in RIBASIM of 90% for both reservoir systems and run-of-river stations.

For the RIBASIM simulation of socio-economic and climate

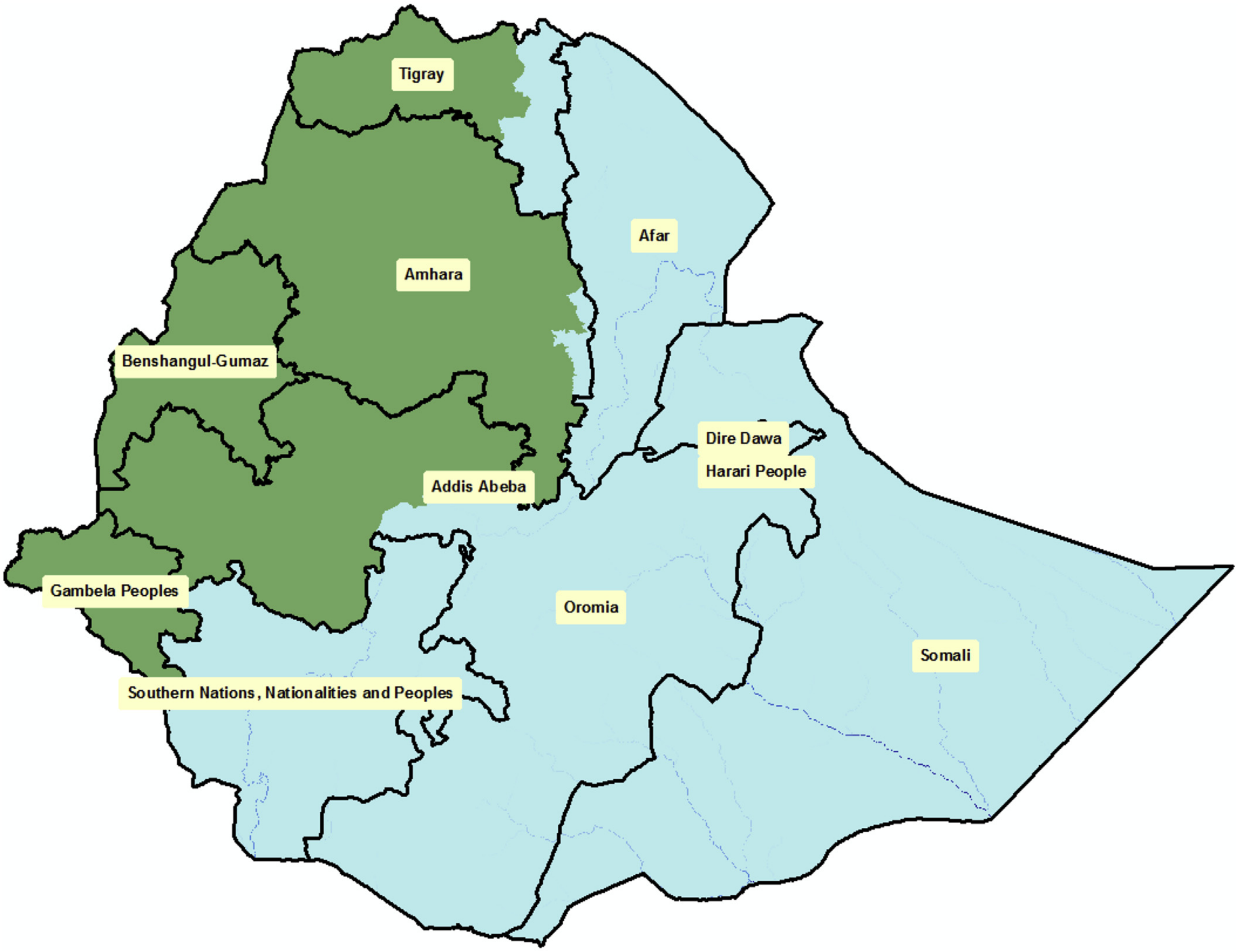


Fig. 2. (a) Blue Nile area in Ethiopia (in green).
(b) RIBASIM model schematization of the Blue Nile river system.

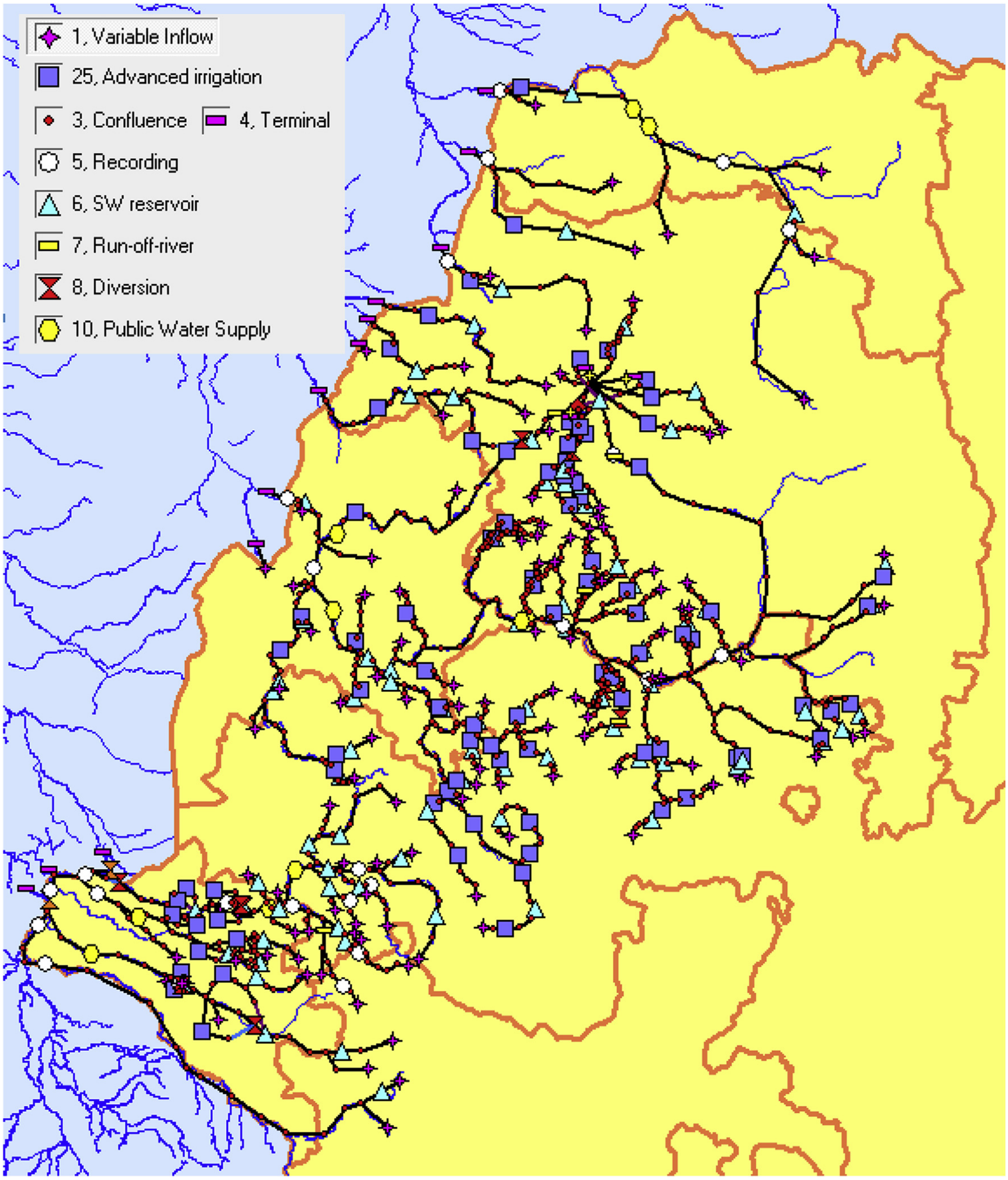


Fig. 2. (*continued*).

scenarios, we formulated one base case (R1) and four hydropower expansion projections (R2-R5), two for the time horizon of 2030 and two for 2050. Scenarios R2 and R3 illustrate the cases, for 2030 and 2050 respectively, without climate change effects, while R4 and R5 are the corresponding scenarios including impacts from climate change (see Table 1). For the latter we use HadGem2 RCP2.6 developed by UKMO (United Kingdom Meteorological Office). Based on an inventory of all existing and foreseen hydropower projects in Ethiopia, we estimate that by 2050 approximately 63% of the total national hydro-electricity generation level will derive from the Blue Nile river system (see [32]). By way of comparison, on the basis of existing public information, the estimated current installed hydropower capacity at the Blue Nile basin only covers 24% of the national figure. In 2015 around 890 MW reservoir-based capacity and 540 MW run-of-river-based capacity was in operation in the Ethiopian section of the Blue Nile. These data provide the

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	14,400 + 750 MW
R3: expansion	2050	Historical	23 SWR +5 RoR	16,360 + 960 MW
R4: expansion	2030	HadGem2	14 SWR +4 RoR	14,400 + 750 MW
R5: expansion	2050	HadGem2	23 SWR +5 RoR	16,360 + 960 MW

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

basis for scenario R1. We project that these figures are raised to 14,400 MW and 750 MW in 2030 (scenario R2), and 16,360 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.

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; see [17]) 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). We assume an expansion of the irrigated area from 75,000 ha in 2015 (R1) to 105,000 and 156,000 ha in 2030 (R2, R4) respectively 2050 (R3, R5). For details on these assumptions we refer to Boccalon [32].

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 Fig. 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, mostly in association with the use of cookstoves. As can be seen, in the near term some energy savings can be realized in this sector, notably through the replacement of current cookstoves by more efficient ones. In the longer run, however, this effect is probably outshadowed 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 Fig. 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.

In Fig. 4 we see the same overall final energy numbers as depicted in Fig. 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 (mostly in solid form, essentially fuel wood and charcoal) 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 (notably cooking) 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 playing a significant role by the middle of the century, but mostly in its 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 level of a few percentage points contribution to overall final energy use.

Fig. 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, as consistent with our findings presented in Fig. 4 where we observed that electrification is a convenient way to decarbonize energy supply.

Depicted in Fig. 5 is also 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

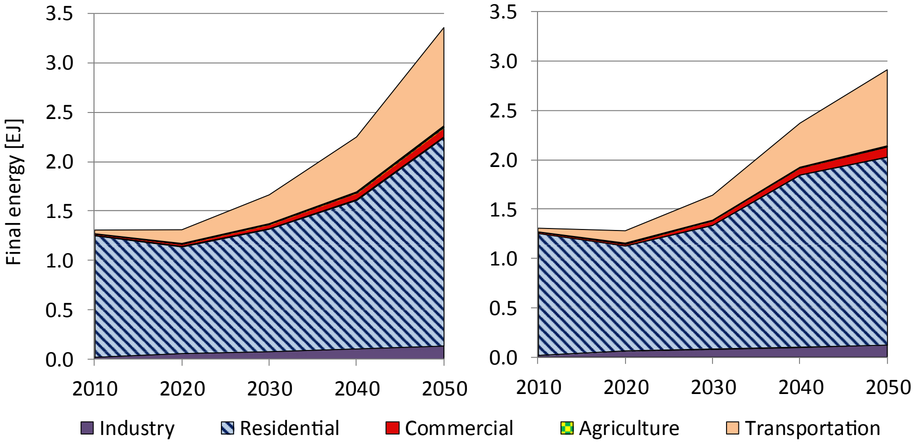


Fig. 3. Final energy use by sector in Ethiopia in two scenarios: baseline (left) and RCP2.6 (right).

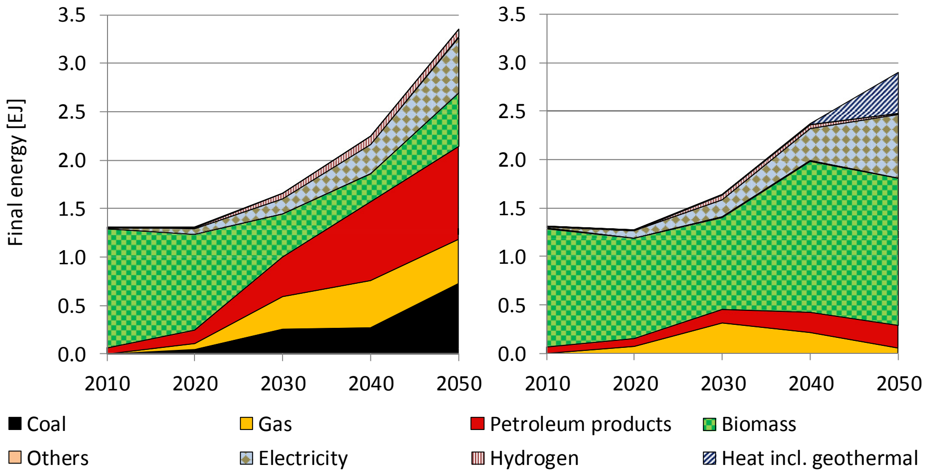


Fig. 4. Final energy use by fuel in Ethiopia in two scenarios: baseline (left) and RCP2.6 (right).

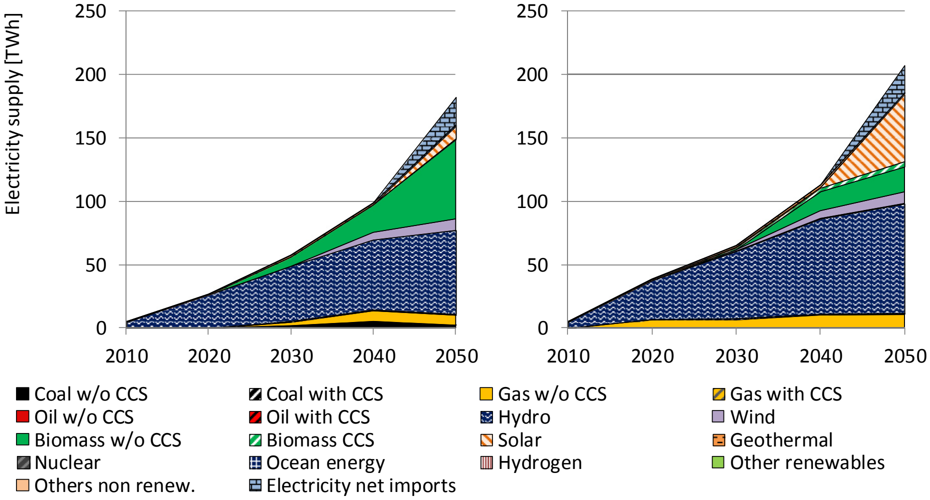


Fig. 5. Electricity supply in Ethiopia by technology and resource in two scenarios: baseline (left) and RCP2.6 (right).

power production by the middle of the century. In the RCP2.6 scenario (right plot) this share could have increased to even close to 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, institutional and financial limitations, as well as in principle limits in terms of water usage for other purposes (but this specific restriction appears not to be binding, as we will see in the next section), may constrain it.

In Fig. 5 we also see that biomass could play a large role in providing electricity services, especially in the baseline scenario (left plot): this is mostly through the combustion of solid biomass in thermal power plants. 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 Fig. 5, stringent climate change control requires an enhanced use of low-carbon electricity generation, for which we think in Ethiopia not only and particularly hydropower but also options like solar and biomass-based energy options could be qualifying candidates. We here further investigate the feasibility of a large hydropower expansion, and leave the realism behind alternatives such as solar and biomass-based technologies for future inspection.

3.2. RIBASIM

Fig. 6 shows the monthly hydropower supply in Ethiopia calculated with RIBASIM under our five scenarios. In scenario R1 we see that on an annual basis on average about 2900 GWh of hydropower is generated, 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 GW h/m). In scenarios R2-R5 we observe a 10-fold increment in electricity generation through hydropower plants in comparison 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 hydroelectricity than in any of the minimum-producing months, in scenarios R2-R5 this difference is in some cases as much as 100%.

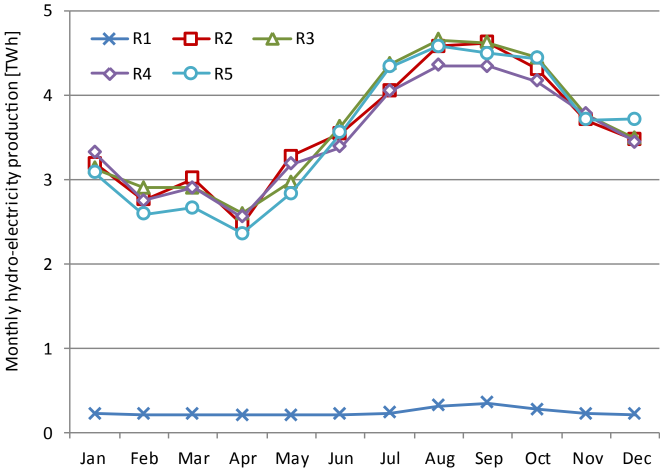


Fig. 6. Monthly total average electricity supply from hydropower reservoirs in Ethiopia's section of the Blue Nile river basin under our five scenarios.

The increase in hydropower production between R1 and R2 is mainly driven by 4 of the 11 additional hydropower plant projects to be commissioned by 2030: the Mendaia, Grand Renaissance, Karadobi and Beko Abo reservoirs, which together account 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 2000 MW installed capacity to the electricity network. This normally would add around 4000 GWh of hydro-electricity production to the entire Blue Nile basin within Ethiopia on an annual basis, or on average around 330 GWh on a monthly basis. The explanation for the fact that this effect cannot be clearly seen in Fig. 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 it will need to internalise the intermittency of renewable energy resources such as solar and wind power: these variabilities must be duly taken into consideration by utilities and operators of plants as well as transmission lines.

Fig. 7 depicts the annual average electricity supply from hydropower dams in Ethiopia in 2030 (R2 and R4) and 2050 (R3 and R5) under the no-climate change and climate change scenarios respectively. The y-axis is cut off at 40 TWh, so that relative differences between scenarios are smaller than they appear in the Figure. As one can see, in 2030 climate change leads to a decrease of around 800 GWh of hydro-electricity generation as a result of climate-change induced modifications in precipitation levels, while in 2050 the corresponding reduction amounts to close to 1200 GWh. One can conclude from a comparison in Fig. 7 between scenarios R2 and R5, that 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 effective rainfall.

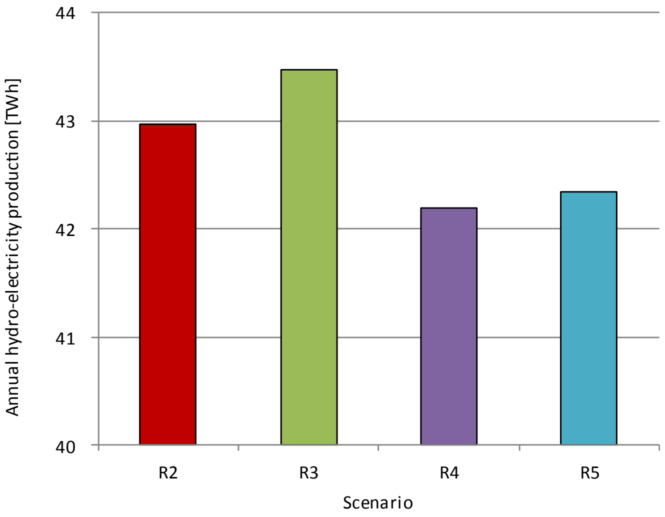


Fig. 7. Annual average hydropower supply from surface water reservoirs in Ethiopia's Blue Nile river basin under scenarios R2, R3, R4 and R5.

To provide a feeling for the importance of time in the availability and distribution of water resources from a multi-sector perspective, Fig. 8 shows – for scenario R2 – a comparison of the timing of precipitation on the one hand, and expected water demand from hydropower production, irrigated agriculture and domestic usage (drinking/cooking, cleaning and sanitation) on the other hand. In all scenarios tested in this study, the RIBASIM operability option to satisfy sectoral water demand has been set to a “proximity to source” mode. As one can see in Fig. 8, water demand for irrigation purposes is at a minimum during the rainy season, while 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 direct need for water other than from rainfall during that period. Reversely, during the dry months (January–April), irrigation demand is at its highest level, and less water is directly available for power production. Water demand for domestic purposes is relatively stable during the year. One observes from Fig. 8 that the peak in hydropower production follows the peak in precipitation with a delay of a couple of months, after which river flow has been accumulated in reservoirs so that dams can operate at nearly full capacity. The results presented in Fig. 8 show the variance of sectoral water demands during the year, as well as the importance of operability rules for determining water distribution across sectors: it matters which operation principles prevail, e.g. “proximity to source”, “first-come, first-served” or “controlled and fractioned supply”. Likewise, the relevance of sectoral water use efficiency becomes clear through Fig. 8, such as with electricity production from hydropower reservoirs.

3.3. Combined insights

In Table 2 we summarize, 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 2500 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 stabilizes likely below a 2 °C global temperature increase), and one in which enhanced climate change materializes (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

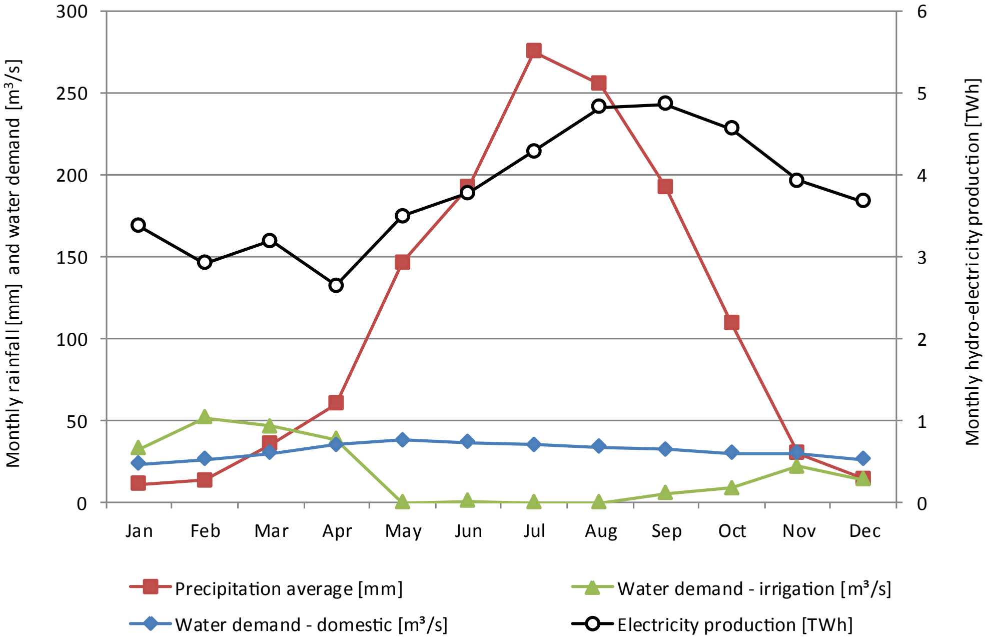


Fig. 8. Comparison of the timing between precipitation and water use for respectively power production, irrigation and domestic purposes in scenario R2.

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

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

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 be explained, however, by the fact that RIBASIM does not include any plants that are not yet in some stage of planning, while opportunities exist for the inclusion of more small-scale hydropower projects. In other words, in order to achieve the large amount of hydro-electricity production that TIAM-ECN foresees, a capacity would need to be installed by 2050 that even goes beyond what is foreseen in current plans and intentions (for a total of 28 surface water reservoirs and 5 run-of-river plants). The explanation for the large amount of hydropower production projected by TIAM-ECN is that it is the level deemed required from the model's cost-minimisation perspective in order for Ethiopia to contribute its share in global climate change control while meeting domestic demand for energy services.

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

The hydropower generation levels depicted in Fig. 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 [9]. Our model outcomes are thus realistic from that point of view. The hydro-electricity generation numbers we calculated also match economically and technically feasible hydropower capacity estimates from other analysts, as well as ambitious long-term national electric power development plans of EEPCO, of around 30 GW in 2050 [16,33]. 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

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

One of the primary aims of this study was to test the possibility of soft-linking energy and water sector modelling tools so as to provide practical instruments for analysis of energy-water nexus challenges and constraints. Through a number of joint input assumptions we enabled the results of our models to be contrasted to each other, even while they followed distinct approaches. We did not make a detailed technical assessment, nor did we perform a feasibility study for large infrastructural development projects. Aspects such as the combined effect of erosion and sedimentation processes, which can substantially affect the energy productivity and life-span of dams, have thus not been taken into account. We have not inspected the optimization of cascaded reservoir operations, potential water losses resulting from irrigated crop diversification, or illegal water abstractions. Possible stringent sectoral policies that might affect the use and distribution of water among users have also been left out of our scenario analysis. All such aspects should be considered in order to draft a compelling and comprehensive policy document; we recognize that our study is limited in this respect.

Through our two approaches we project a high level of hydropower generation in Ethiopia: between 71 and 87 TWh/yr by 2050 in a stringent climate change control scenario in which the country contributes substantially to global efforts to reach the 2 °C target fixed in the Paris Agreement (COP-21, 2015). This elevated level is obtained despite domestic water use increases and irrigated agriculture water demand expansions, and irrespective of possible negative hydrological impacts as a result of climate change induced decreased average precipitation nation-wide. This amount of hydropower production falls within the reach of the estimated national capacity potential of 45 GW, which theoretically (and much depending on specific conditions prevailing at individual reservoirs) could yield a volume of electricity generation between 100 and 200 TWh/yr. On the basis of the dimensions addressed by our two models – energy system costs, national hydrological features and average climate factors – one may be tempted to argue that it makes sense for Ethiopia to pursue its current ambitious hydropower development plan.

Other issues, however, that are beyond our confined methodological scope, need to be considered for such reasoning to hold. For example, Ethiopian authorities should take due account of climate change effects at the local level in terms of potential changes in rainfall during some months or years. We think that these should be researched in greater detail as they might influence flow accumulation in reservoirs and therefore their power production potential. Substantial effort was put into feeding RIBASIM with inputs representing the local effects of climate change in Ethiopia. We use precipitation data from around 200 weather stations in the country, on the basis of which the hydrological features and water availabilities are determined at the sub-district, district and basin level. For modifications in rainfall patterns resulting from 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 Ethiopian Blue Nile sub-basin. Under the HadGem2 RCP2.6 scenario we observed changes in precipitation of almost any value between −70% and +260% depending on the weather station and month under consideration. These translated into average changes between −14% and +27% in 2050, depending on the weather zone. These average deviations were used as input for 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 the model. Given the sizeable efforts required for this, we reserve them for a future study. For further details on how we accounted for precipitation data in RIBASIM, we refer to Boccalon [32].

Other arguments that the Ethiopian government needs to consider before deciding to proceed with its ambitious hydropower plans are a series of conditions and impacts, among which possible environmental effects of large-scale hydropower development. Only when detailed assessments thereof yield results that are aligned with the findings of our study, can it justify pursuing a large expansion of the use of hydropower. Among the environmental effects may not just be the change of natural habitats for animals and vegetation, but also the accumulation of waste products in the water reservoirs and associated emissions of environmental pollutants (including GHGs). Sedimentation from erosion processes in the watershed of rivers may also affect the operation of hydropower dams and reservoirs, and could reduce their lifespan. The ambitious hydropower development plans of the Ethiopian government clearly necessitate independent environmental impact assessments.

Environmental costs may also be imposed on communities living downstream of the dams in Ethiopia, and beyond, which would add to the modification of water availability patterns and intervals. Neighboring countries are likely to see their historical water rights disturbed: countries particularly dependent on Nile water resources, such as in the case of Egypt, have already threatened to take action against the large-scale expansion of dams in Ethiopia. Among the multiple tangible and intangible costs that the construction of large dams entail may also be the required resettlement of people, which adds to their social costs. An almost exclusive reliance on a single power production option makes electricity generation vulnerable to unexpected events. Ethiopia may want to keep its power production diversified, for example to allow for periods of droughts possibly not captured by our current understanding of climate change. Heavy earthquakes are regularly recorded in Ethiopia's seismically active areas, which can endanger hydropower dams and associated tunnels [34,35]. Dams need to be constructed so as to be able to withstand the impacts of the strongest possible earthquakes in the country. Issues of governance also need to be addressed, not only for the safe management and operation of reservoirs and hydropower plants, but also in relation to the fact that thus far many contracts for dam construction have been granted without due competitive bidding. Governance issues may hamper access to financing from international institutions, which further increases the high upfront investment requirements for hydropower development and slows down dam construction programs.

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, does prescribe in detail what these domestic changes in Ethiopia could be, at the level of individual communities, as a result of moderate climate change. 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 could get to a negligible climate change world is the RCP2.6 scenario, since more ambitious scenarios that we attempted to investigate resulted in model infeasibilities. A 70% probability of staying below 2 °C as in RCP2.6 – which we here call moderate climate change – is with TIAM-ECN as close as we could get to RIBASIM's R3 scenario.

Our work has similarities with research undertaken on this topic by Block and Strzepek [16], 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 [16]. 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 average climate change effects as well as expected increases in water demand from domestic and agricultural sectors.

5. Policy implications

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

According to the comparison of model results reported in Table 2 we can see that Ethiopia may not be able to meet its domestic energy demand and climate change control contributions by only relying on the intended hydropower development plans. Based on the results of our investigation we suggest that the Ethiopian government invests more effort into identifying an energy and water sector policy framework that meets internal demand for electricity and water resources while complying with its commitments under the Paris Agreement. This framework should include a broad range of renewable energy sources, energy saving options and water use efficiencies, in order to avoid an over-reliance on natural water resources.

The scenarios investigated in our study and the level of detail used in our computations suggest that possible future climatic trends will not substantially impact hydropower production on a national level, even while non-negligible hydro-electricity generation reductions of around 3% may result from climate change. Yet at the local level individual hydropower plants may be subject to precipitation variability emanating from climate change that could lead to larger hydropower production losses than on average nation-wide. Since there are multiple questions left unanswered in our analysis, such as in terms of the local impacts of climate change during specific time intervals for some hydropower plants, we recommend to continue multidisciplinary research like with 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 independently obtained 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 surface water availability derived from climate and multi-sectoral water demand changes at the sub-district level (RIBASIM). Still, 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. While our study has not found concrete reasons for the Ethiopian government to directly stop pursuing its current ambitious hydropower development plans, we 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 months or years these could lead to substantial reductions in power production levels at some hydro-electric plants and produce conflicting claims for water use by different users. We think that local climate change impacts should be researched in greater detail than the present study has been able to, and be complemented by a social and financial feasibility assessment of realistic investment options and requirements. Since at certain locations hydroelectricity production may occasionally or periodically 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 financial and human capacity investments, as well as extensive planning, institutional plus regulatory development and capacity building. These requirements will need to be complemented by efforts to reduce vulnerability to variability at the local level as a consequence of climate-dependent water availability. Our hydro-electricity generation findings are consistent with those by Block and Strzepek [16], 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 reinforces the reliability of our analysis, as well as our finding that on economic, hydrological and climatic factors alone the Ethiopian government may not necessarily have to immediately stop investing in domestic hydropower development through dedicated national policy schemes.

An important message to the policy making scene, however, is that Ethiopia's government, in view of its intention to heavily invest in hydropower, should be aware of some of the possible negative social and environmental effects of such a massive deployment, and that it takes stock of the potential consequences the large-scale use of hydropower could have on water users within the country and downstream, in South Sudan, Sudan and Egypt. It should probably also not become over-reliant on hydropower, since arguments other than climate change exist (such as major accidents or dam breaches) 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 improved, refined and expanded, for example to allow them to verify whether our conclusions still hold under conditions in which biomass (as we project) also becomes an important part of Ethiopia's energy system. The water requirements thereof will need to be better accounted for in our study. The Ethiopian government has stated 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 growth accurate, and are there more topics that we should account for if we want to further energy-water-food nexus research for Ethiopia? These are the sorts of questions we would like to address in follow-up work.

Acknowledgements

The research that allowed the publication of this paper has been produced with the financial assistance of the European Union in the context of the TRANSRISK project (Horizon 2020 research and innovation programme, grant agreement No. 642260). Additional funding was received from the Dutch Climate Solutions (DCS) programme of the Netherlands Ministry of Foreign Affairs (ECN project No. 52734). The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union or the Dutch government. The authors would like to thank the constructive feedback of several anonymous reviewers, from which it has benefited substantially, as well as of many TRANSRISK and DCS project partners, thanks to whom this article improved a lot. Particularly acknowledged are Monica Altamirano, Duygu Kaynak, Tom Kober, Wil van der Krogt, Anouk van der Laan, Nico van der Linden, Henk Ogink, Frederiek Sperna Weiland and Karl Steininger for their input and efforts enabling the research results reported in this article.

References

[1] IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press, 2011.
[2] IPCC, Climate Change Mitigation, Fifth Assessment Report (AR5), Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press, 2014.
[3] COP-21, Paris Agreement, United Nations Framework Convention on Climate Change, Conference of the Parties 21, Paris, France, 2015.
[4] K. Calvin, L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, E. Kriegler, G. Luderer, P.R. Shukla, The role of Asia in mitigating climate change: results from the Asia modeling exercise, Energy Econ. 34 (Supplement 3) (2012) S251–S260.
[5] P.L. Lucas, J. Nielsen, K. Calvin, D. McCollum, G. Marangoni, J. Strefler, B. van der Zwaan, D.P. van Vuuren, Future energy system challenges for Africa: insights from integrated assessment models, Energy Policy 86 (2015) 705–717.
[6] Energy Economics, in: B.C.C. van der Zwaan, K. Calvin, L. Clarke, Guest (Eds.), Climate Mitigation in Latin America: Implications for Energy and Land Use", Preface to the Special Issue on the Findings of the CLIMACAP-lamp Project, vol. 56, 2016, pp. 495–498.
[7] IEA-WEO, International energy agency (IEA), OECD, World Energy Outlook (WEO), Paris, France, 2014. Special Report, Africa Energy Outlook.
[8] INDC-Ethiopia, Intended Nationally Determined Contribution (INDC) of the Federal Democratic Republic of Ethiopia, 2015.
[9] MWE, Ministry of water and energy, energy study and development, follow-up directorate, "power generation projects open for private sector participation", 2011. Ethiopia.
[10] GEA, Global Energy Assessment, IIASA (Laxenburg, Austria), Cambridge University Press, Cambridge, UK, 2012.
[11] IEA-ETP, International energy agency (IEA), OECD, Energy Technology Perspectives (ETP), Paris, France, 2016.
[12] UN, "Sustainable Energy for All: a Framework for Action", United Nations, the Secretary-general's High-level Group on Sustainable Energy for All, 2012 (New York).
[13] IRENA, International Renewable Energy Agency, Renewable Energy in the Water, Energy & Food Nexus, Bonn/Abu Dhabi, 2015.
[14] J. Arias-Gaviria, B. van der Zwaan, T. Kober, S. Arango-Aramburo, The prospects for small hydropower in Colombia, Renew. Energy 107 (2017) 204–214.
[15] J.P. Ometto, A.C.P. Cimbleris, M.a dos Santos, L.P. Rosa, D. Abe, J.G. Tundisi, et al., Carbon emission as a function of energy generation in hydroelectric reservoirs in Brazilian dry tropical biome, Energy Policy 58 (2013) 109–116.
[16] P. Block, K. Strzepek, Power Ahead: Meeting Ethiopia's Energy Needs under a Changing Climate, Working paper, Columbia University, New York USA, 2012.
[17] UN, United Nations, Department of Economic and Social Affairs, 2017. Population Division, www.un.org/esa/population. last consulted October 2017.
[18] R. Loulou, M. Labriet, ETSAP-TIAM: the TIMES integrated assessment model, Part I: model structure, Comput. Manag. Sci. 5 (1–2) (2008) 7–40.
[19] R. Loulou, ETSAP-TIAM: the TIMES integrated assessment model, Part II: mathematical formulation, Comput. Manag. Sci. 5 (1–2) (2008) 41–66.
[20] S. Syri, A. Lehtilä, T. Ekholm, I. Savolainen, H. Holttinen, E. Peltola, Global energy and emissions scenarios for effective climate change mitigation – deterministic and stochastic scenarios with the TIAM model, Int. J. Greenh. Gas Control 2 (2) (2008) 274–285.
[21] H. Rösler, B.C.C. van der Zwaan, I.J. Keppo, J.J.C. Bruggink, Electricity versus hydrogen for passenger cars under stringent climate change control, Sustain. Energy Technol. Assessments 5 (2014) 106–118.
[22] B.C.C. van der Zwaan, I.J. Keppo, F. Johnsson, How to decarbonize the transport sector? Energy Policy 61 (2013a) 562–573.
[23] I. Keppo, B.C.C. van der Zwaan, The impact of uncertainty in climate targets and CO_2 storage availability on long-term emissions abatement, Environ. Model. Assess. 17 (1/2) (2012) 177–191.
[24] T. Kober, B.C.C. van der Zwaan, H. Rösler, Emission certificate trade and costs under regional burden-sharing regimes for a 2°C climate change control target, Clim. Change Econ. 5 (1) (2014) 1–32, 1440001.
[25] B.C.C. van der Zwaan, H. Rösler, T. Kober, T. Aboumahboub, K.V. Calvin, D.E.H.J. Gernaat, G. Marangoni, D.L. McCollum, A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target, Clim. Change Econ. 4 (4) (2013b) 1–24.
[26] B.C.C. van der Zwaan, T. Kober, S. Calderon, L. Clarke, K. Daenzer, A. Kitous, M. Labriet, A.F.P. Lucena, C. Octaviano, N. Di Sbroiavacca, Energy technology roll-out for climate change mitigation: a multi-model study for Latin America, Energy Econ. 56 (2016b) 526–542.
[27] A. van der Laan, 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, 2015.
[28] Deltares, River Basin Planning and Management, brochure RIBASIM software, Delft, The Netherlands, 2016.
[29] W.N.M. van der Krogt, River Basin Simulation Model, RIBASIM Version 7.00, Model Description & Short Presentation, 2016 (Delft, The Netherlands).
[30] W.J. Collins, 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, Evaluation of the HadGEM2 Model, Met Office Hadley Centre Technical Note no. HCTN 74, 2008. available from, www.metoffice.gov.uk/publications/HCTN/index.html.
[31] C.D. Jones, et al., The HadGEM2-ES implementation of CMIP5 centennial simulations, Geosci. Model Dev. 4 (2011) 543–570.
[32] A. Boccalon, Report on the Water-energy-food Nexus Case Study in the Blue Nile of Ethiopia, internal report, Deltares, 2016.
[33] A. Bartle, Hydropower potential and development activities, Energy Policy 30 (14) (2002) 1231–1239.
[34] F. Kebede, Seismic hazard assessment for the horn of Africa, in: Proceedings of EASEE (the Ethiopian Association of Seismology and Earthquake Engineering) Workshop on Seismic Hazard Assessment and Design of Structures for Earthquake Resistance (EBCS-8: 1995), Addis Ababa, Ethiopia, February 21, 1996, pp. 25–38.
[35] F. Kebede, L.M. Asfaw, Seismic hazard assessment for Ethiopia and the neighboring countries, Sinet Ethiop. J. Sci. 19 (1) (1996) 15–50.