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Power Ahead: Meeting Ethiopia's Energy Needs under a Changing Climate

Paul Block[1] and Kenneth Strzepek[2]

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Abstract

Ethiopia is powering ahead with an ambitious energy development strategy, highly reliant on abundant hydropower potential. A changing climate, including uncertain water supply, however, may pose a salient challenge to meeting expected targets. Bridging the modeling gaps between climate, energy, and economics, and effectively transforming climate changes into economic measures, is an emerging inter-disciplinary field as nations attempt to position themselves for an uncertain future. Such a framework is adopted here to assess energy production and adaptation costs for four climate change scenarios over 2010–49. Scenarios that favor a drying trend country-wide may lead to losses of 130–200 terawatt hours over the 40-year period, translating to adaptation costs of US$2–4 billion, compared to a no climate change scenario. Even given these potential losses, energy development utilizing hydropower appears economically reasonable from this deterministic, sector-independent evaluation. This development is desperately needed, independent of future climate change trends, with the hope of appreciably reducing vulnerability to variability.

Keywords: Ethiopia, energy development, hydropower, climate change, economics

JEL classification: Q25, Q43, Q54

[1]Drexel University, Civil, Architectural, and Environmental Engineering, email: pblock@drexel.edu; [2]Massachusetts Institute of Technology.

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Tables and figures appear at the end of the paper.

UNU World Institute for Development Economics Research (UNU-WIDER)
Katajanokanlaituri 6 B, 00160 Helsinki, Finland

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1 Introduction

Ethiopia's 'white oil'—water—translates into abundant hydropower potential, yet less than 10 percent has been harnessed due to myriad challenges, including financial, political, socio-economic, and climate.Effectively, this translates into 83 percent of Ethiopia's population lacking access to electricity, and 94 percent still relying on fuel wood for daily cooking and heating (Tegenu 2006; Nazret 2008).The Ethiopian government, however, has embarked on an aggressive strategy to massively change course, evidenced by a doubling of the installed hydropower capacity within the last few years, with no indication of decelerating.While other natural sources of electrical generation exist and will likely be exploited, namely wind and geothermal, their expected potential is dwarfed by the 30,000MW of economically and technically feasible hydropower generation (Bartle 2002).Projected demand for electricity is commonly assumed to keep pace with the rapid supply growth, through national consumption and exports to neighboring countries (W. Wolde-Ghiorgis, personal communication 2009).

Achieving the planned energy development strategy will be inordinately exigent, from engineering to economics to policy, but not unprecedented.Implications of climate variability and emerging climate change within Ethiopia are less well understood, further complicating the landscape.This motivates analysis to understand how and to what extent climate change may impact the energy sector through hydropower, given the current development strategy.Alternative development strategies to mitigate climate risks may ultimately be warranted, but those decisions are beyond the current scope of this work.The focus here is to assess planned hydropower development under various future climates, and costs associated with restoring hydropower generation to baseline (no climate change) conditions.

A further impetus for this study is to feed into a sector- and country-wide economic analysis totaling all expected benefits and losses to the country under a changing climate, including sectoral feedbacks.This is achieved through a computable general equilibrium modeling process, outlined by Robinson et al. (2011) in this issue.Ethiopia has been selected as one of seven country case studies for a World Bank project focusing on the economics of adaptation to climate change (World Bank 2011). Bridging the modeling gaps between climate, energy, and economics, and effectively transforming climate changes into economic measures, is an emerging inter-disciplinary field of exceptional interest as nations attempt to position themselves for an uncertain future.

2 Ethiopia's climate

Ethiopia is marked byexceptional climate variability, particularly precipitation, both spatially (Figure 1) and temporally (Figure 2). For the western half of the country, which receives significantly greater rainfall, and where most of the hydropower projects are planned, uni- or bi-modal precipitation patterns are evident.The main rainy season, the *Kiremt*, occurs from June-September, and is part of the larger East African monsoon, initiated by a northward shift of the inter-tropical convergence zone (Griffiths 1972;

Gamachu 1977; Block and Rajagopalan 2007).Inter-annual variability of precipitation, particularly over westcentral Ethiopia in the Blue Nile basin, has been investigated extensively (see, e.g., Eklundh and Pilesjo 1990; Seleshi and Demaree 1995; Camberlin 1995; Conway 2000; Osman and Sauerborn 2002; Segele and Lamb 2005; Block and Rajagopalan 2007). Sea surface temperatures in the Pacific Ocean, specifically those in the El Niño–Southern Oscillation region, and regional influences are predominantly responsible for modulating this variability.

The vast majority of ensuing streamflow contributes to the larger Nile basin, a conglomerate of nine African nations.Other basins feed into Kenya, Somalia, Djibouti, or are endorheic, however, none extend directly to the sea, as Ethiopia is land-locked.Transboundary considerations are thus a critical component of national and regional water development.

Predicted changes in precipitation at climate change scales vary across the global circulation models (GCM) available (see Figure 3 in Giannini et al. 2008).The majority of models, however, tend to favor increasing annual precipitation averaged over the country as the century progresses.Hydrologic studies, typically narrowed to the Blue Nile basin, provide a mixed review of impacts on streamflow, specifically at mid-century (e.g., Kim et al. 2008; Yimer 2009; Beyene et al. 2010), however, uncertainty is not trivial given the insufficient number of streamflow gauges and minimal monitoring basin-wide.

3 Hydropower development plan

Existing and planned energy projects were drawn from the Ministry of Water Resources' Water Sector Development Program (2002) and basin master plans, the Ethiopian Electric Power Corporation's (EEPCo) long-term development plans, and personal communication (Hunter 2001; EEPCo 2004; Ministry of Water Resources et al. 2004; Ethiopian Rural Development and Promotion Center 2007; Embassy of Japan in Ethiopia 2008; Agriconsulting and Mid-day International Consulting 2009; Hailu 2009; EEPCo staff 2009).As previously noted the vast majority of these represent hydropower sources, with some smaller-scale alternatives considered.Numerous future hydropower projects are still in pre-planning stages, and spatial locations are therefore approximate (Figure 3).

Two development plans are considered: the first targets 13 gigawatts (GW) installed by 2030 and 17 GW by 2050.The second plan, newly proclaimed, is much more ambitious, aiming for installations of 20 GW by 2030 and 30 GW by 2050 (Figure 4).Both plans consider identical project sequence, capacity, and costs, but the latter shifts project construction forward in time to meet the accelerated target.As 2050 spans well beyond specific ministerial plans, best estimates are employed.

4 Model framework

The model framework consists of a linked climate-hydrology-hydropower system to transform climate information and change into development benefits and energy production for comparing various scenarios (Figure 5).

4.1 Climate and hydrology simulations

Five simulations are evaluated here, including one base and four potential climate changes for the period 2010–49.The base embodies no climate change trend, expressing only observed variability, representing one plausible projection.The GCMscenario combinations selected to produce potential climate changes include the US Geophysical Fluid Dynamics Laboratory-A1b, the US National Center for Atmospheric Research (NCAR)-A1b, Australia's Commonwealth Scientific and Industrial Research Organization-A2, and NCAR-A2, representing the national driest and wettest and global driest and wettest averages respectively, as determined by the climate moisture index averaged across the 2045–55 decade (Robinson et al. 2011).This subset, while not fully inclusive, is intended to provide a sense of potential ranges in outcomes.

The base simulation simply consists of observed monthly precipitation and temperature data from 1961–2000, representing a stationary climate, based on the University of East Anglia Climate Research Unit's data (Mitchell and Jones 2005).To create the four climate change simulations, the overall precipitation trend from each GCM is extracted and added to the monthly base observations.This limits the reliance on GCMs to reproduce precipitation at high temporal resolution, a characteristic that is not currently well reproduced (Xu 1999). GCMs are typically more robust in representing temperature, however, so direct projections are retained.

A transformation from climatic variables to hydrologic variables is performed with the CliRun rainfall-runoff model (Yates 1996; K. Strzepek, personal communication 2011).The 0.5° x 0.5° gridded one-bucket conceptual model is calibrated over Ethiopia to produce monthly streamflow and evaporation for ensuing use in the hydropower model.

Additional details regarding formation of the climate and hydrology projections are available in Robinson et al. (2011).

4.2 Hydropower model

An expanded version of the Investment Model for Planning Ethiopian Nile Development (IMPEND, Block and Strzepek 2010) is selected to simulate hydropower production throughout Ethiopia.IMPEND is classified as a planning tool with operationallevel detail to help define feasibility and expectations of project choice.It is a deterministic, standalone energy model, but may be looped over many climate simulations seamlessly.The model is driven by monthly streamflow and net evaporation, varying from year to year, as prescribed by the hydrology simulation file.Each dam and reservoir combination are modeled individually, brought online according to the development strategy, and assumed to operate at their design height, passing the full hydrograph of flows (no additional storage or releases). Prohibiting additional reservoir storage is suboptimal at the local scale, but eliminates the need to explicitly model transboundary agreements, which are not well defined.Energy production commences upon the year of commissioning.Construction and capital costs are assumed divided over the five years prior to commissioning.Outputs include monthly and net hydropower energy production and annual project costs.No variables within IMPEND are independently varied—they only vary as a result of the climate and hydrology inputs, supporting the goal of understanding the effect of climate changes on energy benefits.

Physical data to construct IMPEND, including dam, reservoir, and power characteristics, are provided by the water sector development program, basin plans, and a United States Bureau of Reclamation preliminary study (Bureau of Reclamation 1964).Model calibration and validation draws on historical streamflow records publicly available (e.g., Bodo 2001).

Non-hydropower energy sources are also explicitly included in the hydropower model, although not subject to climate variations.

4.3 Adaptation strategy

Energy adaptation for the climate change scenarios considered is founded on meeting or minimally exceeding the exogenous annual base energy production (for each development plan separately) throughout the 40-year simulation.This is accomplished in the model by considering the same set of energy development projects, and shifting the year of commissioning as necessary to augment or reduce energy production.Thus, if in any year energy production in the climate change simulation is inferior to the base simulation, the next scheduled project(s) is brought online that year to increase supply until the base simulation is matched or exceeded.Once an energy project is brought online, it must remain online.Alternatively, if a project is scheduled to come online, yet energy production under the climate change simulation without the addition of the new source can meet the base simulation, then the project may be delayed.

5 Climate change and hydropower modeling results

5.1 Implications to the existing hydropower development plans

Total annual energy production differences between the base and climate change simulations is difficult to distinguish prior to 2030, but become increasingly obvious in later decades as the number of projects and climate change effects increase (Figure 6–7).Not surprisingly, the inter-annual variability patterns across 2010–49 are not dissimilar, as all simulations are constructed on the identical observed monthly precipitation pattern (i.e., base simulation); it is the added GCM trend from the climate change scenarios that offer uniqueness.In general, wetter (drier) GCM trends favor increasing (decreasing) energy production, especially evident in later decades.By 2049, there is notable separation in production between simulations, both annually and aggregating over the entire time period (Tables 1–2).In comparison to the base simulation, the two NCAR model simulations demonstrate a surplus, while the Goddard fluid dynamics laboratory (GFDL) and the Commonwealth Scientific and Industrial Research Organisation(CSIRO) model simulations reveal a deficit.

Given the limited information resulting from a single simulation (per model), a simple stochastic approach is undertaken to capture the uncertainty in inter-annual variability and exhibit potential energy production outcomes.Even by 2049, it is likely that inter-annual variability will account for a larger proportion of the total variance in production than the climate change trend.Quantifying this expected range therefore becomes desirable.

For demonstration, only the GFDL model trend (driest scenario) for the first development plan is considered. 20 unique sequences are constructed by bootstrapping and assembling 40 years (of monthly values) from the base simulation record.The GFDL trend is then added to the 20 sequences to form the plausible simulations.Although the transition from year to year is not explicitly captured, December to January being the dry season and reservoirs operating only at their design height both limit this effect.

Energy production outcomes resulting from the 20 GFDL simulations reveal a sizeable spread (Figure 8), offering more information than the deterministic simulation alone.Total energy production summed over the 40 years varies from 1242–1358 TW_hrs; total energy production in 2049 varies from 36– 63 TW_hrs, a not-insignificant range.An even greater range of uncertainty may be expected under the second, more ambitious development strategy.This type of probabilistic information, and an understanding of acceptable risk in the Ethiopian energy sector, may guide long-term decision-making, and warrants additional attention.

5.2 Adaptation

Adaptation to climate change is achieved by shifting projects forward in time to meet or exceed base energy production.No changes in timing are allowed for committed projects through 2013.For simulations favoring wetter conditions, project commissioning may actually lag base energy development, clearly presenting the opportunity for additional, unplanned energy production.This phenomenon, however, is not exploited in this study.For simulations favoring drier conditions, additional hydropower plants to those listed in the current Ethiopian development plan may be required to meet the adaptation strategy in the far future.In those cases, a ‘generic’ project is appended to the development plan covering the difference.Generic project costs are based on existing and planned hydropower capacity-cost relationships, values presented in current literature, and average Ethiopian topography and streamflow conditions.It should also be noted again that the alternative sources of wind and geothermalenergy, introduced more dramatically in the second development plan, are considered unaffected by climate changes.The validity of this requires further study.

All deterministic simulations are evaluated under the less ambitious development plan, however only the driest (GFDL) model is assessed under the more ambitious plan, to gauge an upper estimate on potential adaptation costs.

As anticipated, simulations requiring projects to commence earlier than planned result in greater overall development costs, even when discounting is considered (Figure 9–10, Table 3). For both development plans, this becomes quite evident after 2015.The difference in cumulative costs between the base and driest climate change simulations is not trivial; for the GFDL model scenario, a US$2.4 billion (US$4 billion) adaptation cost is projected under the less (more) ambitious development plan.Contrarily, if the climate tends toward a wetter regime, and the development plan is such as to only meet base production, a surplus of US$3 billion is possible under the first development plan.Neither of these estimates is absolute, as climate uncertainty is not well captured, but do begin to relate magnitudes and discrepancies between wet and dry trends in adaptation planning.

6 Discussion and conclusions

This research is a starting point for bridging the modeling gaps between climate, energy, and economics, to transform climate changes into economic measures.The outcomes of this research are relevant for energy development and planning, but also as inputs to a wider economic analysis, as performed with a computable general equilibrium model(Robinson et al. 2011).

The primary recommendation surfacing from this analysis is to continue on the ambitious development trajectory as planned.This development is desperately needed, independent of future climate change trends, and will require significant investment and capacity, with the hope of appreciably reducing vulnerability to variability.A proper mix of project scale and scope is not discussed here, but will be vital to a healthy sector.

Further detailed analysis is necessary to recommend regional energy project focus and sequencing based on climate change trends, both temporally and spatially.This may be accomplished by building on the current set of models and close engagement with ministry officials and relevant institutions to prioritize.Ideally this approach would foster a balance between early development of no-regrets projects and selection of projects targeted to most alleviate poverty and vulnerability (if mutually exclusive).

It is worth noting that there is a fair amount of ‘noise’ in the early decades, especially for the first development plan.Cumulative cost curves (Figure 6) donot become clearly separated until sometime after 2030; the NCAR-A2 model cumulative costs continue a back-and-forth with the base throughout the period.Strong conclusions regarding behavior in the early decades should be withheld, as this is really a sorting-out period, and climate change trends are less well established.This ambiguity may be better expressed though a full stochastic assessment accounting for climate uncertainty.

While this study certainly gives indication to the effects of climate change on energy, specifically hydropower, many aspects of the analysis to date are simplified.Tradeoffs between sectors (energy, agriculture, urban use) are not considered for a finite water resource (i.e., lost hydropower or other economic use). Development and adaptation costs do not account for the true value of water nor promote economic efficiency. While fully incorporating these aspects is quite advanced, including some semblance of them is highly recommended prior to adaptation (or perhaps even development) recommendations.

The current set of models do not account for changes in the frequency and magnitude of precipitation events due to the inability of GCMs to provide this resolution confidently. Floods and droughts are major drivers, yet due to data limitations, cannot be resolved in future projections sufficiently.If extreme events are to become more common, adaptation costs here are very likely underestimated.Future GCM versions will hopefully improve resolution, which may be carried through the ensuing models.Nonetheless, policies ignoring adaptation should not be adopted; adaptation is still a matter and topic of the present.Even amidst this and other uncertainties, there remains tangible information to provide direction.Uncertainty should imply flexibility in development strategies, infrastructure, and operational management through time.

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Table 1: Summation of energy production for the base and climate change scenarios under the first development plan

	Total energy		Difference with baseline	
Simulation	TWh/40yrs	TWh in 2049	TWh/40yrs	TWh in 2049
Base	1435	56	-	-
GFDL a1b	1305	48	-130 (deficit)	-8
CSIRO a2	1440	52	5	-4
NCAR a2	1515	60	80	4
NCAR a1b	1605	68	170	12

Table 2: Summation of energy production for the base and climate change scenarios under the second development plan

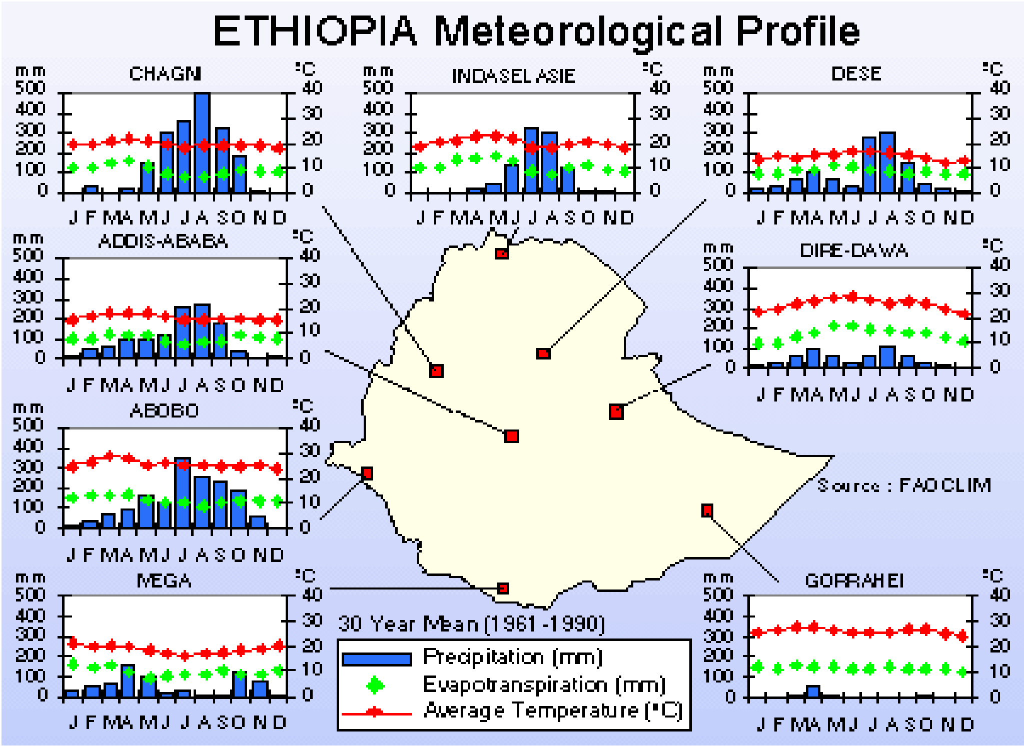
	Total energy		Difference with baseline	
Simulation	TWh/40yrs	TWh in 2049	TWh/40yrs	TWh in 2049
Base	3430	152	-	-
GFDL a1b	3220	139	-210 (deficit)	-13
NCAR a1b	3730	175	300	23

Table 3: Summation of discounted (2010) hydropower project costs over 40-year simulation for the base and climate change scenarios

	Total cost (US$ billion)		Difference with baseline (US$ billion)	
Simulation: 1st development plan	0% disc	5% disc	0% disc	5% disc
Base	22.8	12.4	-	-
GFDL a1b	25.2	14.4	2.4	2.0
CSIRO a2	23.7	13.1	0.9	0.7
NCAR a2	22.9	12.4	0.1	0
NCAR a1b	19.8	11.6	-3.0	-0.8
Simulation: 2nd development plan	0% disc	5% disc	0% disc	5% disc
Base	68.7	33.7	-	-
GFDL a1b	72.7	37.7	4.0	4.0

Note: disc = discount rate.

Figure 1:Ethiopia meteorological profile



Source: From FAO/GIEWS website.

Figure 2: All Ethiopia average annual precipitation

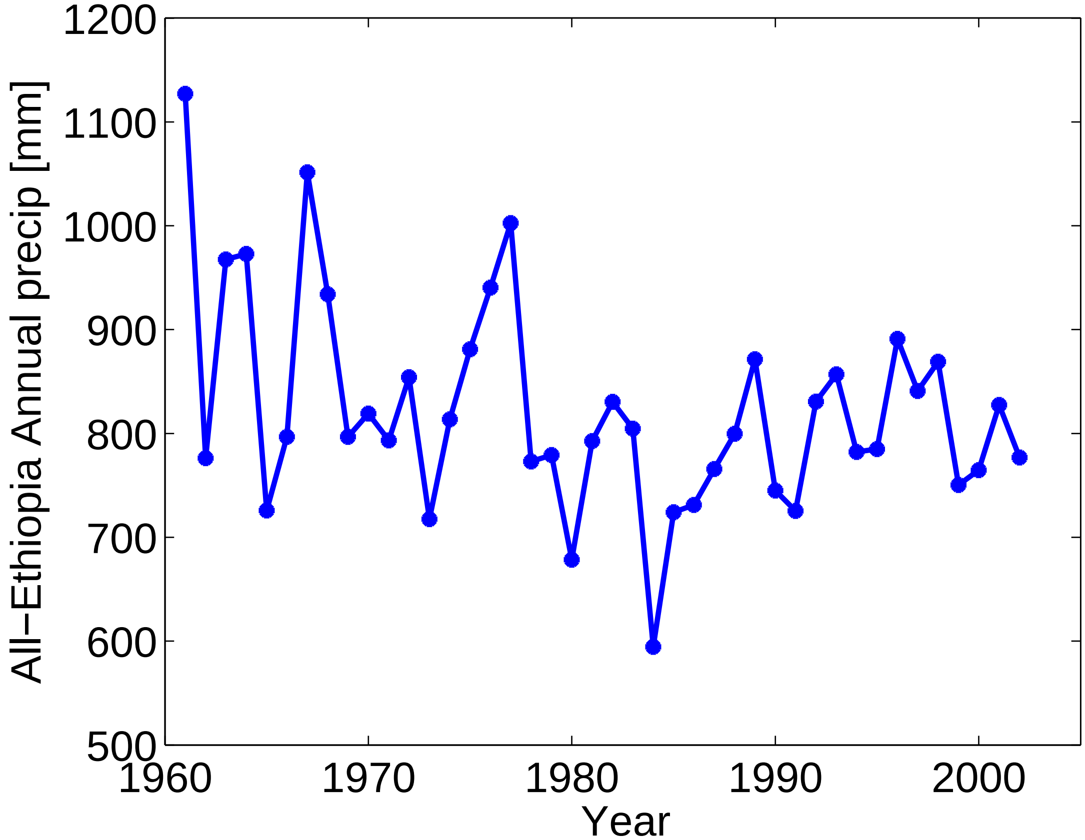


Figure 3: Existing and Planned hydropower projects considered within Ethiopia

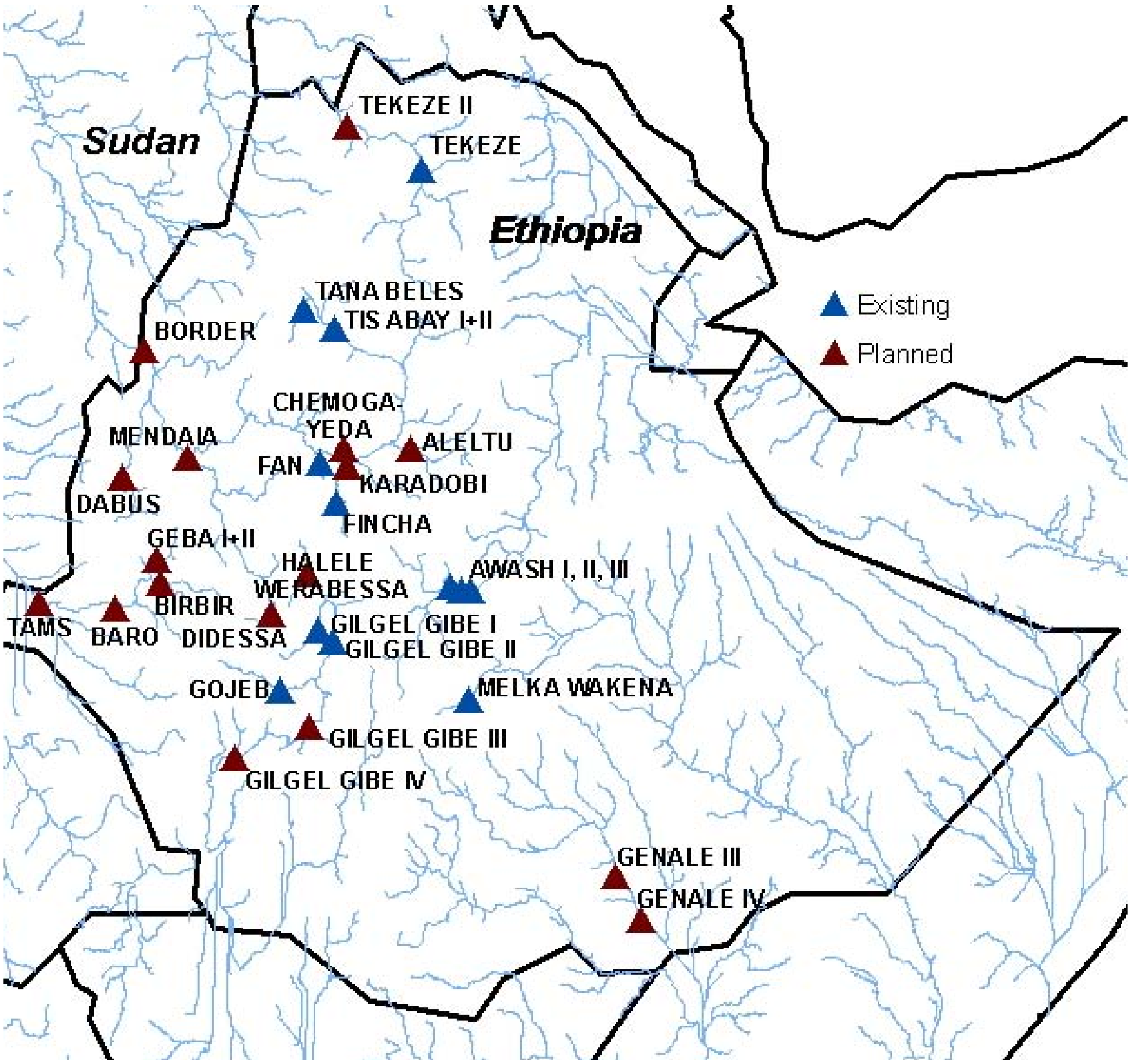


Figure 4: Ethiopia first (dot-dash) and second (dash) energy development plans

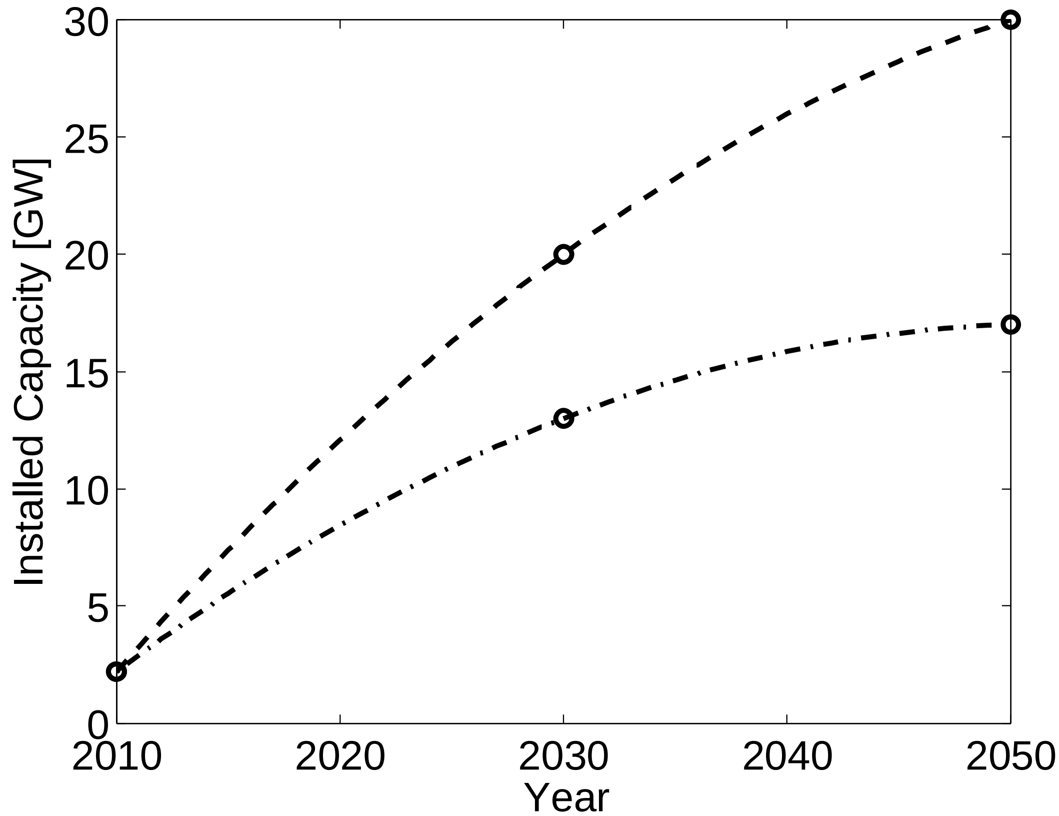


Figure 5: Climate-hydrology-energy modeling framework

Figure 6: Annual energy production for the base and four climate change scenarios under the first development plan

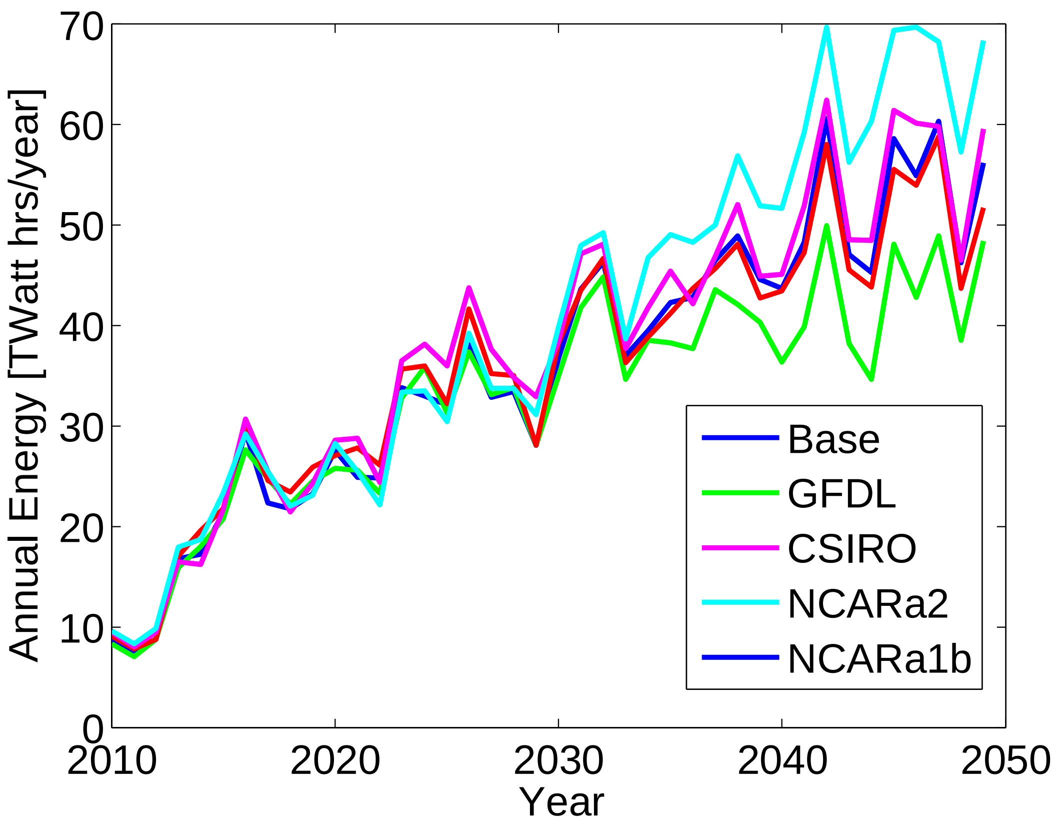


Figure 7: Annual energy production for the base and four climate change scenarios under the second development plan

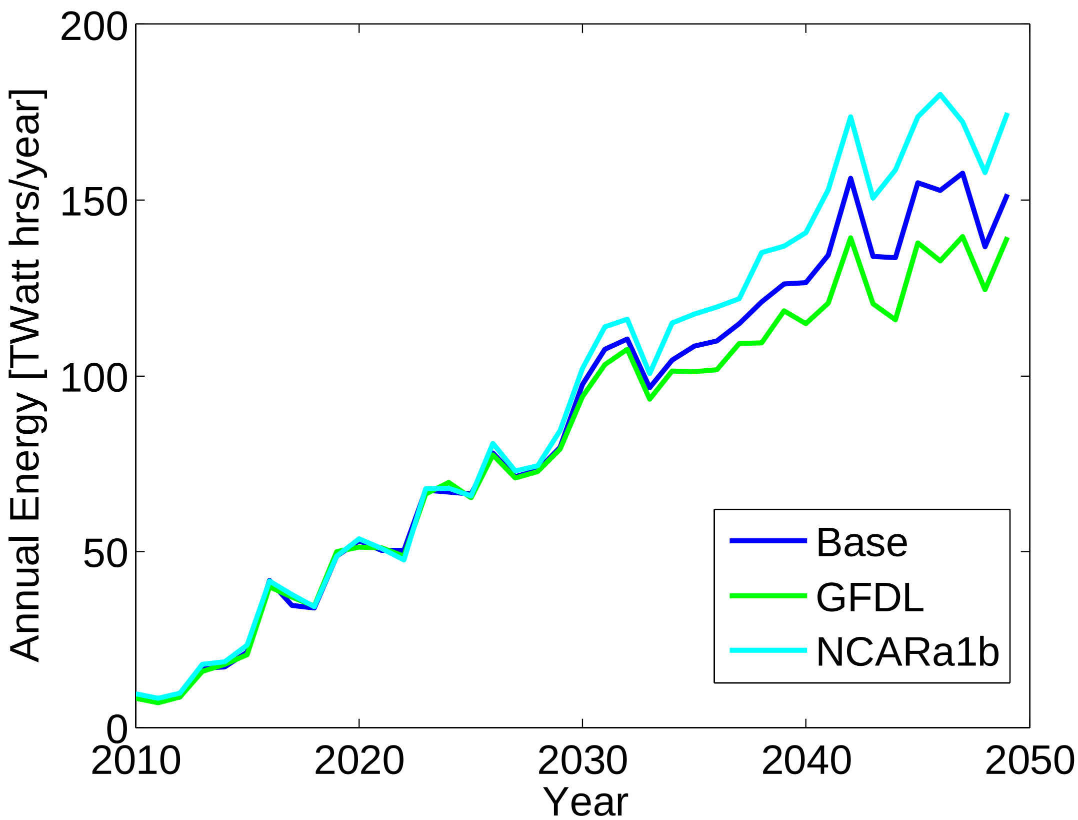
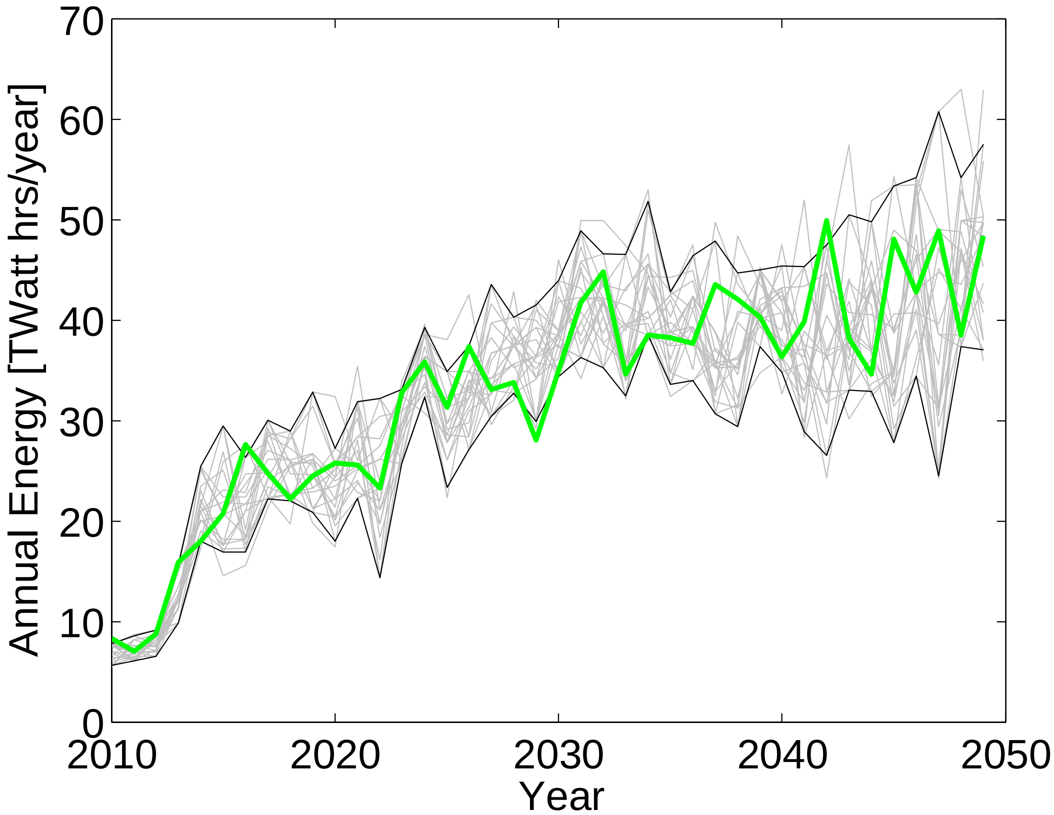


Figure 8: Twenty simulations (thin gray lines) of annual energy production for the GFDL climate change scenario under the first development plan



Note: Black Lines are the 5th and 95th percent of the Simulations; Green Line is the Single GFDL Simulation from Figure 6.

Figure 9: Cumulative discounted project costs at 5% for the base and four climate change scenarios under the first development plan

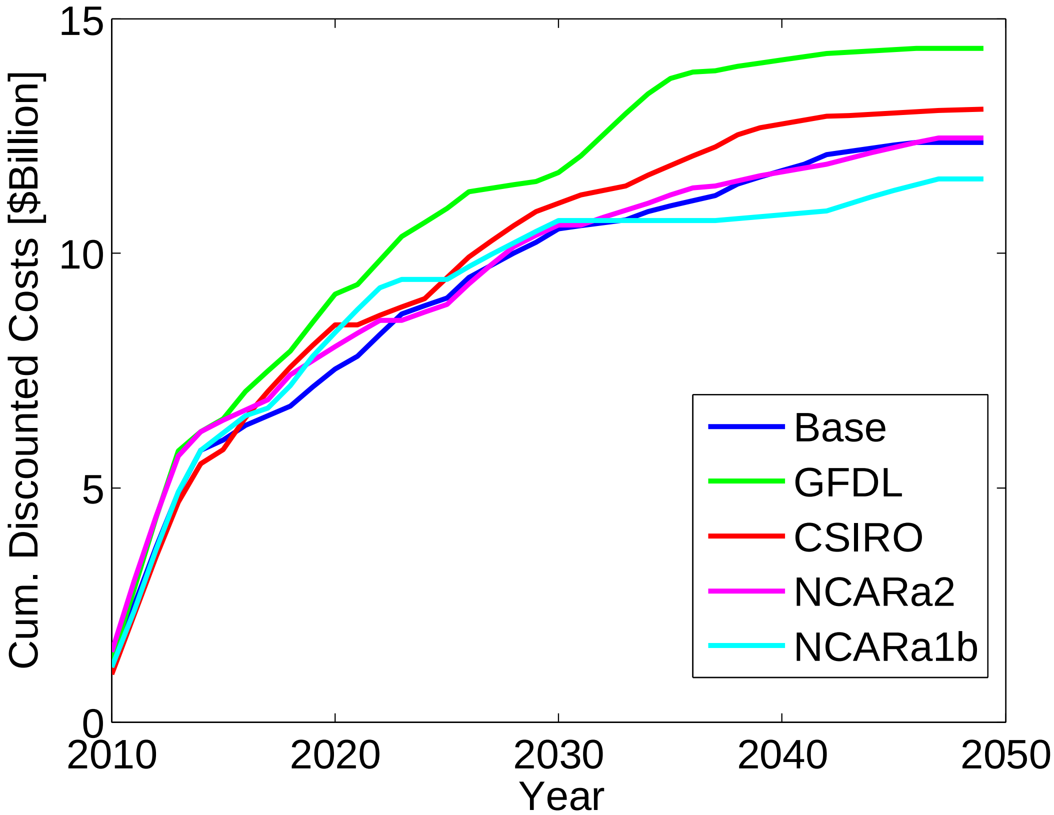


Figure 10: Cumulative discounted project costs at 5% for the base and four climate change scenarios under the second development plan