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Power system sensitivity to extreme hydrological conditions as studied using an integrated reservoir and power system dispatch model, the case of Ethiopia

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HIGHLIGHTS

- Apply integrated reservoir and power system dispatch to study power grid challenge.
- Electricity costs grow by a factor of 4 as the inflow goes from moderate to low.
- Some scenarios, e.g. low inflow, lead to significant electricity supply shortage.
- Focus policymaking and planning on transitioning to climate change adaptive system.

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ABSTRACT

Extreme weather events expose electricity industry to diverse risks. Global warming will increase vulnerability to extreme weathers, such as drought. In this paper, we examine the susceptibility of Ethiopian power systems to extreme hydrological conditions using an integrated hydro reservoir and power system dispatch model. The result shows that hydropower could help in achieving the least cost generation of electricity by 2017. However, the cost of electricity was found to significantly vary with various factors. It was found that, excluding cost of unserved energy, the low inflow scenario presents a situation where cost of electricity is approximately 4 times higher than the moderate inflow. Electricity price is currently cheap and stable due to governments pricing strategy. Consequently, the cost borne by the nation's economy could be seen from annual cost of dispatch, which increases from approximately 1 billion USD per year at the reference scenario to about 4 Billion USD for the low inflow scenario. The dispatch cost will be above 8 folds if the cost of unserved energy is included. This shows that the power system is poorly resilient against climate change impact. Thus, we recommend that policymaking and planning focuses on transitioning to climate change adaptive system.

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1. Introduction

Electricity generation depends on water resources. More specifically, hydropower generation strongly depends on rainfall and evapo-transpiration process, which affects the available water discharge at the power plant. Similarly the thermoelectric generation varies with water temperature and its availability, due to thermal generators reliance on water as cooling and generation fluid. As a result, impact of extreme weather, such as drought, on energy industry has been a focus of several studies [1–13]. Researchers have shown that drought based climate impact on power system appears in the form of increased outage, reduction in generation efficiency, shortage of cooling water, higher mean water temperature, increased evaporation from water surface, etc. [1–13]. Consequently, negative impact of drought on electricity supply, demand and costs were reported [1–17]. Currently, there are universal consensuses that climate change exposes the electricity industry to diverse risk. Yet, despite the reported drought patterns and their negative impact on energy supply, very few have made a comprehensive study into its influence on electricity generation. Many of these studies focus on impact of water shortage and temperature on thermoelectric generators [3–5,8–13,15]. Only few of these studies have included the impact on hydropower [1–3,5,6,11,12]. In addition, these studies cover mainly regions that fall in the

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temperate zone, with significantly different hydro-climatic condition to the location of this study. Several projections show that impact of climate on water resource and energy system varies depending on geographic locations [1–3]. For example, hydropower potential is projected to increase in northern Europe (Norway and Russia) as opposed to the anticipated significant drop in Southern and South Eastern Europe [1]. Similarly, in [2] stream flow is projected to increase in Northern Europe, Canada, Central Africa, India and Northeastern China. In regions covered by those studies, the shares of hydropower in power system are also very small (roughly less than 20%). The anticipated impact for places that has larger dependence on hydropower is expected to be higher than those places dominated with thermoelectric generators. In Africa, the two countries, namely Ethiopia and Ghana, that produce more than 75% of their electricity from hydropower has suffered adverse effect of drought [17,18]. Similarly, industrial customers in Brazil were subject to a contract that requires paying more than twice the cost of electricity paid by other customers due to the severe impact of drought on the hydropower generation potential (which provides more than 83% of the electricity need) of that country in 2014[19]. But there are no study that specifically evaluated the potential impact of drought on predominantly hydropower systems. The present study examines the impact of extreme hydrological events using data set from Ethiopian power systems. Due to the following two reasons, the Ethiopian system provides the best scenario to examine the severity of the impact.

First, hydropower plants supply currently about 98% of the electricity need in Ethiopia. So far, the nation exploited only 5% of the estimated 45GW hydropower potential [20]. It also has an estimated capacity of 1035 GW wind and 7 GW geothermal potential [20] as well as approximately 5.2 kW h/m^2 daily average irradiance over most places of the country [20]. At present, several large-scale generation projects, such as the 6000 MW Grand Ethiopian Renaissance Dam (GERD), and long distance transmission lines are under construction. Some of these transmission lines are cross-country projects that are expected to aide power trade with its neighboring countries through the facilitation of the regional consortium of utilities called Eastern African Power Pool. Due to the significant unexploited hydropower potential, the national master plan shows that hydro remains the biggest source of electricity in years to come [20,21]. Regionally, with its significant renewable potential, Ethiopia and Kenya are expected to be the energy hub of the established Eastern African power pool.

Second, climate projections show that Ethiopia will be one of the hotspots of climate change in sub-Saharan Africa [22,23]. But the implication of climate variability is not well understood. Hydrological projections are uncertain but anticipate increased stream inflow in the western part of the country but the pattern will be significantly variable [22,23]. Moreover, Ethiopia was ranked among the top vulnerable countries to extreme weathers, such as flood and drought [22,23]. In [21], it was shown that climate change driven drying scenario could have significant impact on its hydropower potential. But the study did not specifically evaluate the impact of extreme events, which is already affecting energy supply of the nation [18] and other countries with similar system [17,19]. Historically, extreme events, such as droughts, are already common in Ethiopia, with about 12 extreme droughts being reported in the past century [18,22–24]. Ironically, 7 of these events occurred since 1980. There have also been dozens of local droughts with equal devastating effects [24]. Moreover, it is projected that climate change increases the nation's vulnerability to extreme weather [22,23]. These historical events as well as the corresponding hydrological data sets, and the dominant hydropower generation infrastructure presents the Ethiopian system as a good network to evaluate the impact of hydrological variations on similar power systems and the level of its vulnerability to such extremities.

This study, therefore, applies an integrated reservoir and power system dispatch model to study the sensitivity of power system to extreme weathers. The optimization model that we have constructed for this purpose will be applied to dispatch hydro-reservoirs and the entire power systems to meet the expected demand by 2017. We selected 2017 because of the large-scale hydropower plants, such as Grand Ethiopian Renaissance Dam (GERD) and Gilgel Gibe III, to be committed on that year. At the same time, in the year 2017, significant non-hydro generators such as wind, a waste-to-energy power plant, biomass plants and sugar factory cogeneration systems are expected to be online. This provides the opportunity to evaluate the complementarities of other resources to hydropower. While the coordinated dispatch is one of the oldest areas of study, it is applied to the Ethiopian system for the first time. At the same time, it is rarely employed to study the sensitivity of power system to extreme hydrological conditions. In addition to studying the impact of hydro-variability by applying co-optimizing dispatch model, this study will also assess the impact of various factors, - such as a delay/partial delay of some of the on-going projects, load scenarios- on the Ethiopian power system reliability. To the author's knowledge, the impact of hydro-variability on hydro-dominated power systems is reported for the first time. Drought impacts on non-hydro power plants are not included in this paper due to the present limited role of non-hydropower plants. We believe that this paper will inform policymaking and planning to prepare for significant impact of hydro-variability on the power systems with significant share of hydropower.

2. An overview of Ethiopian energy industry

As one of the third world countries, Ethiopia's energy supply and consumption is heavily inefficient. Majority of the nation's energy need (approximately 92%) comes from biomass resources [25–30]. The remaining energy need comes from electricity and imported petroleum. In the past decades, Ethiopia has reported an economic growth in real GDP increase. The reported economic growth, as is usually the case, was followed by increase in energy demand. The average annual growth in electricity demand from 2012 to 2013 was approximately 14%, while petroleum consumption increased by 87% from year 2000 to 2009 [25,26]. Ethiopia's electricity consumption per capita is approximately 60 kW h on the year 2012, which is significantly lower than the 521 kW h average per capita of sub-Saharan Africa [25,26]. According to some estimate only 23% of the population has access to electricity services in 2012 [25,26]. In addition to low level of electricity access, the existing electricity service is also unreliable. In recent years, the government of Ethiopia has devised an ambitious policy goal of reaching a universal electrification by 2037 [20]. To achieve that goal, the national master plan set-out a schedule of several transmissions and generation projects [20]. Ethiopia faces significant challenges while working towards the aspired goals. The 2.3% per annum population growth, scattered population distribution in rural areas, shortage of skilled man power, weak institutional capacity, financing challenge, etc, are some of the challenges that the energy industry is facing.

Lack of local research activities has also opened significant knowledge gap that is required to reduce the involved risk. For example, the electric industry traditionally follows three planning stages. These are: (i) long term planning, which is focused on identifying appropriate generation and transmission resource requirement for a distant years (usually 3–5 year or longer); (ii) medium term-planning or sometimes seasonal planning deals with guiding marketing decision and operation of the power systems by looking up to 1–2 years ahead; (ii) short-term planning deals with day-to-

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