Assessing Climate Change Vulnerability of Microgrid Systems

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***Abstract*—In this paper, we build a framework to assess climate-change impacts on a power system. In order to appropriately capture the uncertainty of the climate change's multi-dimensional impacts, we argue that the multiple representative scenarios need to be set. Therefore, we developed a data-driven method to select representative scenarios instead of using the random-sampling method. We explain why the data-driven method is more appropriate for the research on the climate change than the random-sampling method. We adopt our framework to analyze an island nation's micro grid system. The research demonstrates that the climate change can significantly impacts this nation's electricity generation cost, energy security, and environmental performance.**

***Index Terms*—Climate change, Generation capacity risks, Island micro grid, Vulnerability.**

I. INTRODUCTION

The power system is not only one of the main contributors for greenhouse gas (GHG) emissions but also a vulnerable system to the climate change. Climate change can significantly threaten the reliability of a power grid by increasing demand and reducing the reliability of transformers and transmission capacities [1]. In particular, climate change can seriously threaten the generation capacity in some countries. For instance, the drought in Brazil has already threatened the electricity supply costs due to reductions in hydro generation capacity factors.

We assess the power-grid system's vulnerability due to the climate change in an island nation. In this island nation, the electricity generation substantially relies on bagasse, a byproduct of sugarcane crops. In particular, around 30% of the electricity generation capacity during the peak-load period comes from bagasse fueled generators, which continue to generate electricity by using imported coal when the bagasse storage runs out [5]. Generation expansion plans for the island contemplate utilizing additional bagasse plants. However, the production of bagasse is sensitive to climate and therefore to its change. If less bagasse is produced, more of the power production will be fueled by coal, which will lead to various impacts in the system.

Micro-grid operation in an island power system has attracted significant interests in power systems [3,4,5,8]. Many studies have addressed the question of how much and what mix of renewable energy can be installed. Fan et al. found that the 14% of power in Pulau Ubin in Singapore can be supplied by solar PV [3]. Cai and Li suggested that the renewable-energy penetration level can achieve 40% on China's Hainan Island if a smart grid system can be developed to integrally operate the installed generation capacity of wind power, household PV, and energy storage [8].

The impacts of climate change are complex and uncertain. Therefore, the framework assessing climate change's impacts must appropriately capture representative climate-change scenarios and associated impacts on island nation's micro grids. We develop a framework to analyze the climate-change impacts on the micro-grid system. We use this framework to

- demonstrate that climate change creates generation uncertainty scenarios, and
- assess the climate-change impacts on the micro grid's emissions, electricity costs and prices on the island.

As the main contribution of this paper, our framework comprehensively structures multiple modules for analyzing the interaction between the climate change risks and micro-grid operations. The framework consists of: (a) a module examining the climate change's influences on a power system; (b) a module capturing uncertainties of multiple climate-change scenarios, and (c) a data-driven process to simplify power dispatch representations. Instead of simulating the dispatch by directly using daily load data, we first use a data-mining method to select the representative load curves and then only consider the dispatch outcomes given the representative load curves. Because the climate change's impacts are long term, we should focus on the representative load curves, which reflects the nature of a region's demand, rather than every day's exact load curve. This simplification also allows us to examine much more climate-change scenarios than when every day's dispatch is simulated.

The rest of the paper is organized as follows: Section II introduces the background information and data sources for the island nation's micro grid; Section III presents the framework for climate-change impact's assessment and its modules; the results and discussions are included in Section IV; Section V concludes the paper.

II. Background and Data

A. Background the the electricity system in the island

The island nation[1] is located near the east coast of southern Africa, which is a climate-change vulnerable region. Climate change progression in this island nation is significant and faster than the prediction of the International Panel on Climate Change (IPCC) [16].

Electricity is mainly generated from oil, coal, and bagasse. The corresponding market shares in 2015 are 31%, 45%, and 13%. Bagasse is counted as a biofuel and plays a dominant role in the renewable-energy component for this island. The remaining share of renewable energy includes hydro, wind, and solar power, which totally correspond to only 6% of the total generation. According to this nation's energy plan, the generation by bagasse will reach at least 17% of the annual generation by 2025.

In the island nation, electricity is provided by a primary power supplier, the Central Electricity Board (CEB), and several independent power producers (IPPs). IPPs generate electricity with bagasse when the cropping season, which starts at the beginning of July. When the bagasse runs out, IPPs' generators are fueled by coal. In particular, the IPPs' generators have different generating capacities when using bagasse in contrast when using coal [7,15,16].

The most population of this island nation concentrates in the northwestern region. Electricity in the southwestern region is mostly utilized by the agricultural sector and low-density populations. In Fig. 1, we present the simplified transmission network on this island. The transmission network is operated at a nominal voltage of 66 kV while substations are operated at a lower voltage of 22 KV. Bolded numbered circles indicate the substations where IPPs locate at.

B. Data

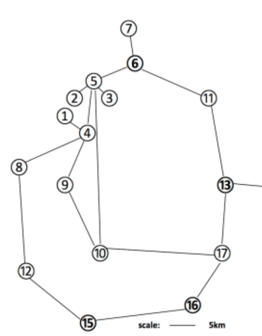

Figure 1. Transmission network topoloty in the island

[1] The official data provider for this paper has requested the name of the island nation be withheld.

The CEB provides the detailed information of the grid network including grid topology, generator characteristics, aggregated load profiles at two-hour time steps, and the voltages of the transmission lines and substations [7]. We collect sugarcane-production data from 1961 to 2013 from the statistic division of the Food and Agriculture Organization of the United Nation (FAOUN). The data about the climate are collected from [15] and [16].

III. A Framework to Estimate the Grid Climate Vulnerability and Plan for Climate-Change Adaption

A. Framework

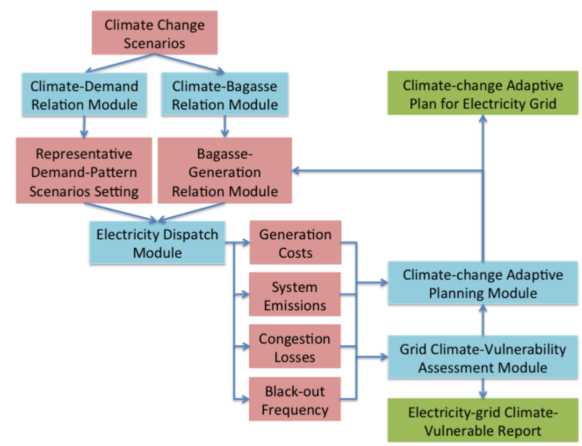

Figure 2. Framework to assess the climate vulnability of a electricity

In Fig 2, we present our framework for the assessment of climate change's impacts on a micro-gird system in a region that is vulnerable to climate change. The climate-change scenarios firstly are set according to the real climate change during the last several decades and the report of International Panel on Climate Change (IPCC). The possible climate-change scenarios then are input into two modules. The first module is used to estimate the demand change caused by climate change. The estimated demand change is used to determine the representative daily load pattern. The second module is used to estimate the impacts of climate change on the total production of sugarcane as well as bagasse generation capacity. According to the scenario setting, we simulate the electricity dispatch and measure the electricity system's costs, reliability, and emissions given different climate change scenarios. The results are used to evaluate the climate vulnerability of the electricity grid system.

B. Climate change scenario setting

During the last 40 years, the average temperature in this island nation keeps a growth trend. Until 2015, the annual average temperature has already been about 0.7°C higher than the 1981-99 average level. In contrast, the IPCC predicts that the average temperature will only averagely growth 0.8°C until 2030[17]. Thus, it has a high potential that the climate change progress is quicker than the IPCC's average prediction.

Therefore, we consider three climate-change scenarios. In the optimistic scenario, the temperature will increase by the average speed of the IPCC's prediction. In the average scenario, the temperature will increase by the maximum speed of the IPCC's prediction. In the pessimistic scenario, the temperature will increase by the speed we observed during the last decades. In Table I, we summarize the temperature-increase extents in different years in three scenarios on the basis of 1951-60 average level [17].

TABLE I. CLIMATE CHANGE SCENARIOS
(TEMPERATURE INCREASE EXTENT ON THE BASIS OF 1951-60 AVERAGE LEVEL IN °C)

	Year			
	2015	2030	2045	2060
Optimistic	+0.80	+1.00	+1.20	+1.40
Average	+0.80	+1.30	+1.65	+2.00
Pessimistic	+0.80	+1.60	+2.25	+2.90

C. *Impact of climate change on bagasse-generation capacity*

The climate change impacts the generation capacity of bagasse generators by fluctuating the production level of the sugarcane. Three main elements of the climate determine the sugarcane productions, which are the temperature, precipitation, and humanity. However, the precipitation in this nation does not significantly change in this period. In addition, the current precipitation level is far higher than the threshold, lower than which the precipitation begins to impact the sugarcane production. Furthermore, we lack the information about the average humidity, which is usually highly correlated with the temperature and precipitation. Therefore, we only use the temperature to predict the future production of sugarcane.

The sugarcane production is correlated with the yearly temperature as shown in Fig. 3. The figure demonstrates that the average temperature maintained the growing trend during the last 40 years. Coincidently, the sugarcane production level keeps decreasing.

According to the average crop-rotation period of sugarcane, we estimate the linear correlation between 7-year average productions with the temperature deviations [14]. In Addition, we notice that the average sugarcane production decreases faster when the temperature deviation is higher than 0.5°C than the average decrease rate. This indicates that 0.5°C can be the threshold by exceeding which sugarcane's production is more sensitive to the temperature increase. Therefore, we examine two cases. In one case, which is referred as the "moderate case", sugarcane production decreases with the temperature growth by the average rate of the last 40 years. The relation between sugarcane production and temperature growth is estimated by the black line in Fig. 3. In the other case, which is referred as the "catastrophic case", the production of the sugarcane decreases with the growth of the temperature by the rate when the temperature deviation is higher than 0.5°C, which is estimated by the black dashed line in Fig. 3.

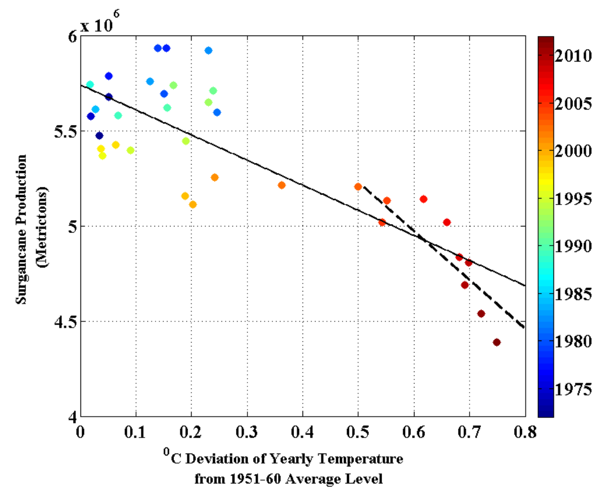

Figure 3. Correlation of temprature and surgarcane production

In Table II, we summarize the production level of sugarcane in different scenarios. We can observe that even in the average scenario of the moderate case, the production level will decrease by more than one third until 2050. If the temperature grows as fast as in the past decade while the temperature-production relationship follows the catastrophic case setting, this island nation will no longer be viable for the sugarcane industry. Even in 2030, the bagasse generation capacity can decrease by half due to the sugar-cane production's decline.

TABLE II. SUGARCANE PRODUCTION LEVEL IN DIFFERENT SCENARIOS (10^6 TONS)

	Year	2020	2030	2040	2050
Moderate Case	Optimistic	4.7	4.4	4.2	3.9
	Average	4.7	4.0	3.6	3.1
	Pessimistic	4.7	3.6	2.8	1.9
Catastrophic Case	Optimistic	4.4	3.9	3.3	2.7
	Average	4.4	3.0	2.0	1.0
	Pessimistic	4.4	2.2	0.3	0

Considering multiple scenarios is important to estimate the impacts of climate change on a power system. For example, the model that simulates the relation between climate change and sugarcane production is limited by the data that we have. Therefore, the scenario setting based on the correlation may overestimate or underestimate the impacts of climate change on bagasse-fueled generation capacity. However, because we consider multiple scenarios, we reduce the potential for the existence of the estimation bias caused by the data limitation. In the future work, we will collect more detailed agricultural information to support a more complicate accurate climate-agricultural module.

D. A data-driven approch to select the representatitive days

Considering multiple scenarios requires us to develop a method to select representative load profiles instead of simulating every day's dispatch.

We develop a data-driven method to select representative daily load levels and patterns instead of randomly sampling a few days from the dataset. For each season (January-March, April-June, July-September, and October-December), we use K-means clustering method to classify daily loads. The clustering results conclude that the aggregated load pattern in the island nation can be classified into two clusters for each season. Then, representative day's load for each season is the weighted average of the two cluster centers. The weight of each center is the proportion of the days in that cluster to the total days in the season.

We chose this approach because of two reasons. First, we need a set of standard consumption behaviors for the estimation of long-term highly uncertain impacts. Because daily loads include a lot of noisy information caused by other issues, directly using daily load data is inappropriate for the estimation of the individual impacts of climate change. Second, the cluster center is more representative than random sampling days. Furthermore, we can design associated robust analysis according to the distribution of the distance between a point and corresponding cluster center.

In this research, we do not include the impact of load growth in order to estimate the pure impacts of the climate change on the generation side. It is quite straightforward to incorporate load growth and optimal planning but we leave it for future work.

E. Daily dispatch model

According to the generators' technical data and fuel cost data, we estimate each generator's cost function by using the method in [9,10,11,13]. We assume the hydro electricity generators' fuel costs are zero and treat them as negative load. Because of the data limit, we do not include the impact of the cycling effects of fuel generators in our research. We also do not include the impact of transmission losses in this model. We solve a DC optimal power flow (DCOPF) problem to calculate the system dispatch plans and associated economic and environmental impacts. In the DCOPF problem, we minimize the hourly system cost with the constraints of phase angle, transmission capacity limits, generators' max capacity limits and minimum generation limits, and load balance condition [6].

We use CVX, a software package that implements convex optimization in MATLAB, to solve the DC Power Flow [12]. For each representative day, we simulate their dispatch plans twice. One is to simulate the system costs and emissions when IPPs use bagasse. The other is to simulate the system costs and emissions when IPPs use coal to fuel their generators.

IV. RESULT AND DISCUSSION

The direct impact of climate change on the island nation's grid system is that this nation must purchase more coal abroad to compensate the decline of bagasse generation capacity. In Fig. 4, we present how much additional coal need to be purchased from the international coal market due to the climate change. If the climate-production relation following the catastrophic case setting, the coal purchased abroad is much higher than that when that relation following the moderate case setting. These results reveals the big risks to the power system caused by the possible non-linear impacts of the climate change on the agriculture sector. Furthermore, the climate change at most will force this island nation to purchase additional six hundred thousand tons of coal. The total costs of purchasing coal at the price level in 2014 will be more than 30 million dollars, which is about 18% of the total generation cost of this country.

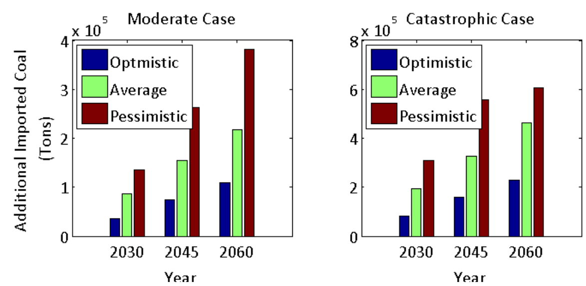

Figure 4. Additional coal purcased to adapt climate change

The impact of climate change on the total generation costs is complicated. IPPs have higher generation capacities when they use coal than when they use bagasse. When the bagasse generation capacity declines, the coal will not only replace the bagasse but also parts of diesel generation capacities. Consequently, in some scenarios, the decline of the bagasse generation will result in the decrease of the generation costs because the cost increase caused by coal replacing bagasse is less than the cost saving caused by coal replacing diesel. Otherwise, the decline of the bagasse generation will result in the increase of the generation costs. We present the impact of the climate change on total generation costs in Fig. 5. The big difference between generation costs in different scenarios suggests significant risks to the island nation's economy. In fact, the total-cost increase caused by climate change is around 0.8% of this country's nominal gross domestic production (GDP).

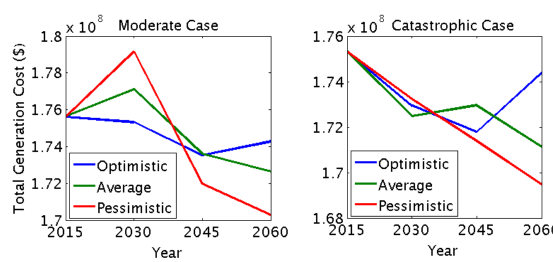

Figure 5. Correlation of temperature and surgarcane production

In this island nation, all coal must be purchased abroad [5,7]. Therefore, the climate change threatens this nation's energy security. In particular, the country plans to expand its bagasse generation capacity to improve their energy independence. The results suggest that this plan will expose the nation to an even higher energy-security risk.

In addition to the impact on the generation cost, the climate change also will increase the total GHG emissions from this island nation's grid system. In Fig. 6, we present the additional CO_2 emissions from the electricity generation in this island nation due to the climate change. We emphasize that the emission increases because the climate change leads coal not only to replace bagasse but also to replace diesel. By 2020, climate change can at most result in additional 700 thousand tons of CO_2 emissions, which is around 20% of the nation's total GHG emissions in 2014.

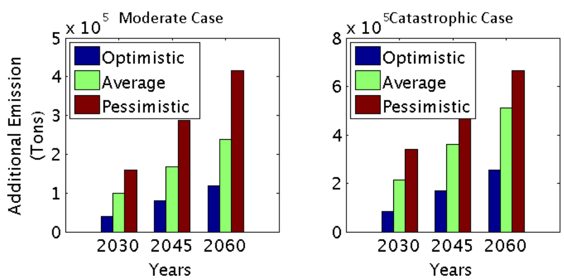

Figure 6. Correlation of temperature and surgarcane production

V. CONCLUSION

In this paper, we develop a framework to systematically analyze the climate change's impacts on a power system. By adopting the framework, we examine the climate change's impacts on an island nation's micro grid system. The results demonstrate the significant impacts of the climate change on this nation's energy security, economy, and environmental performance.

The essential challenge of analyzing the climate change's impact is how to capture the uncertainty. In order to capture the uncertain nature of the climate change's impact, we explore various climate-change scenarios. In order to computing-economically simulate multiple scenarios, we propose a data-driven method to select the representative load profiles.

The proposed framework and methodologies are useful for multiple further studies. In future works, we will explore how to perform planning in the presence of climate uncertainty. In particularly, we will include renewable-energy and storage technologies when we consider the impacts of the climate change. In addition, we will model how the climate change impacts the demand side

VI. ACKNOWLEDGEMENT

We give our appreciations to the Central Electricity Board for their assistance and data sharing.

VII. REFERENCE

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