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Energy System Planning towards Renewable Power System: Energy Matrix Change in Cuba by 2030

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Abstract: Since 2013, the biggest Caribbean island, Cuba, has been undertaking an energy matrix change. There is a strong political intention to replace fossil fuels by renewable energy and improve efficiency and security of the national energy system. By 2030, 24% of electric power shall be produced from renewable sources. Transition from centralized fossil fuel fired power system towards distributed renewable generation based system requires changes to conventional energy planning and system design procedures as well as physical structures of the national energy system. This paper introduces three analysis axis: Scenario building for future supply-demand balance, scenario for a 100% renewable energy system for Cuba, and a roadmap from existing power system to the system with high share of distributed renewable generation. This work is a part of European Union funded Erasmus+ project "Capacity Building for Renewable Energy Planning in Cuban Higher Education Institutions", CRECE.

Keywords: energy matrix, renewable energy, energy planning, distributed generation

1. INTRODUCTION

Current electric power system (EPS) in Cuba relies mainly on mineral oil-based fuels and natural gas fired generation. Cuba has its own oil and gas production, but e.g. on 2013, 38% of crude oil used for energy production was imported. At present, renewable energy sources (RES) based generation covers only 5,2% of the total electricity production. The national power system is managed by the national electric power company Unión Eléctrica de Cuba (UNE). UNE's total generation capacity is app. 6000 MW consisting of 2600 MW of heavy fuel oil fired large scale steam power plants, 600 MW of natural gas fired large scale gas turbine plants, 1100 MW of smaller scale medium/light fuel oil fired steam and engine plants, and 1100 MW of diesel engine plants. The RES based generation is composed of 470 MW of biomass fired boilers, 63 MW hydro, 10 MW wind, and 10 MW solar PV. (JICA, 2016).

Cuban government has instituted a series of energy sector reforms focusing on balancing of costs, improvement of energy efficiency, reduction of risks in energy distribution, increasing international cooperation, and implementation of renewable energy technologies. By 2030, energy consumption is estimated to increase app. 40% from 20 TWh to 28 TWh, and the share of RES should rise to 24% of total production. On 2030 renewable power generation resources are planned to consists of app. 1400 MW biomass fired thermal capacity, 700 MW solar PV capacity, 700 MW wind power capacity, and 120 MW small-scale hydropower. The estimated shares of different sources of generated power on 2030 are depicted in Figure 1.

Policy decision for changing Cuba's energy matrix encloses several issues such as energy economy, environmental issues and energy efficiency. Transition to renewable energy production will reduce the amount of imported fuels and harmful environmental impacts. Furthermore the distributed generation (DG) structure instead of the centralized one will reduce transmission losses (Bouhouras and Labridis, 2012), and improve system resilience for hurricane attacks and other locally occurred natural disasters.

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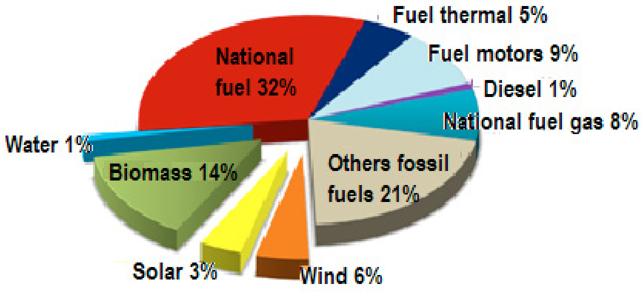

Figure 1. Electric matrix on 2030. Source: (Guerra, 2014)

Increased share of RES in future power system brings several challenges to system planning and operation. Weather dependence of wind power and solar PV generation increases uncertainty in the premises of system design, which should be taken into account in decision making about required generation capacity and reserves, need of energy storages, control strategy and flexibility capacity of the system. Increased share of RES in the power system increases control needs (load tracking + intermittent generation) while the share of controllable thermal generation capacity is typically reduced. In addition, replacement of synchronous generators having massive rotational energy storages in their rotors by power electronics based converters will reduce inherent inertia of the power system, and will make it more sensitive for serious problems about maintaining the system frequency. On the load side, transition to energy efficient frequency converter based control of electric drives have the same effect on system inertia. Voltage control in DG systems differs from conventional voltage control in centralized approach as well as safety system design, because in DG systems direction of electric current in lines may change depending on the state of the system. (Galvan et al., 2016).

That is why the massive introduction of the RES into the Cuban power system is not only a political issue, but also a deep analysis of system planning methodology, control design, and operation issues are needed. Power system designers need new skills to be able to meet all the challenges raising from the new type of DG power systems with high share of renewable intermittent generation. European Union funded Erasmus+ project "Capacity Building for Renewable Energy Planning in Cuban Higher Education Institutions", CRECE, focuses on the development of these skills together with Cuban universities, energy research institutes, and the national power company. The project consortium consists of 13 partners from Finland, Germany, Spain, Costa Rica, and Cuba.

The structure of this paper follows the main technical research questions of the CRECE project, the topics/problems that should be studied and solved on the way to the new power system. The first step in energy system planning is based on scenarios about the future energy needs and resources, how much energy is needed and what are the options to produce it. Chapter 2 introduces the LINDA-modeling tool (Long-range INtegrated Development Analysis) for scenario building of future energy systems, and CubaLINDA model developed for Cuban energy system. In a long run, the final destination will be a 100% renewable energy supply system. Chapter 3 introduces a scenario how this could be achieved. Chapter 4 discusses about the grid structure and control issues in the future Cuban energy system. Chapter 5 summarize the findings and sets the next steps of the CRECE-project and the "Cuban energy revolution".

2. SCENARIO CONSTRUCTION FOR FUTURE SUPPLY-DEMAND BALANCE

Scenarios for the future demand of electricity can be constructed in several ways. One way is to divide the electricity demand in different components and predict the future changes in these components. A simple way of looking at the demand is to divide it in two components, economic activity and electricity intensity, and electricity demand = economic activity (Gross Domestic product, GDP) × electricity intensity of production. This can further be decomposed into sectoral components based on the sectoral division of economic production (such as e.g. agriculture, industry, services, transport).

Since the electricity intensity in different sectors is quite different, the future electricity demand depends considerably on the structure of the economic growth. In the Cuban case, the electricity intensity of industrial sector is 3-4 times higher than that in service sector. It means that electricity demand will be higher if the future economic growth is dominated by industrial development. Figure 2 shows examples produced with CubaLinda model (Luukkanen et al., 2015a, Luukkanen et al., 2015b) of electricity demand in two scenarios with equal GDP growth; BAU, Business as Usual scenario, and IND, Industrial scenario where the industrial growth is faster resulting to faster growth of electricity demand (see Del Pino Caro et al., 2016, Vazquez et al., 2016). The CubaLinda model is constructed by using one-hour resolution data.

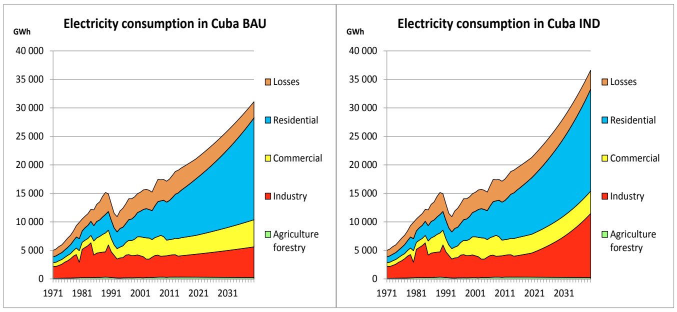

Figure 2. Two scenarios for electricity demand in Cuba with equal total GDP growth. In BAU scenario service sector growth is higher while in IND scenario industrial growth is higher.

The case scenarios for electricity production are assumed to follow the governmental plans for the increase of the share of renewable energy sources up to 24% in 2030. In the BAU scenario, the installed renewable energy capacity consist of 700 MW solar, 700 MW wind, and 1400 MW biofuel based generation.

The predicted electricity production by different power plant types in the BAU scenario is shown in figure 3. The "New technology" means here natural gas fired combined cycle units and light fuel oil and diesel oil fuelled engine plants.

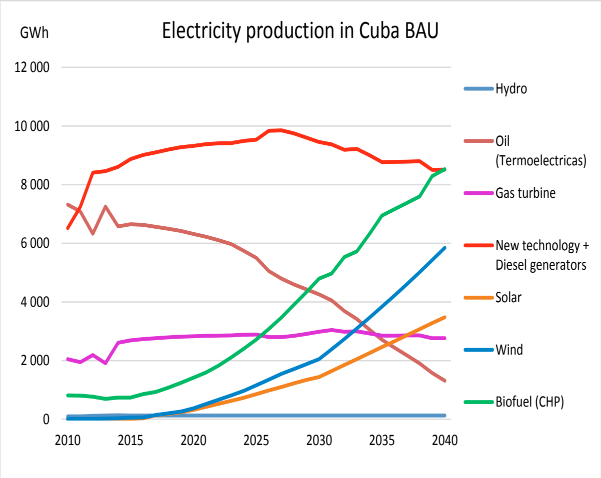

Figure 3. Electricity production by different power plant types in the BAU scenario.

Power generation has to follow instantaneous fluctuations in electricity demand. With the increased share of intermittent renewable supply, the controllable power production has to be able to ramp up and down with higher operation range and change rate compared with conventional system structure. Figure 4 shows the ramp rate envelope for the BAU scenario in 2030. The ramp rate is calculated from the hourly estimated change of residual power (demand – solar, wind, and biomass based generation) in six hours' time horizon over one year. The ramp rate calculation, especially for maximum and minimum values, is suggestive, because smoothing differences in local fluctuations in solar PV and wind generation profiles are not taken into account.

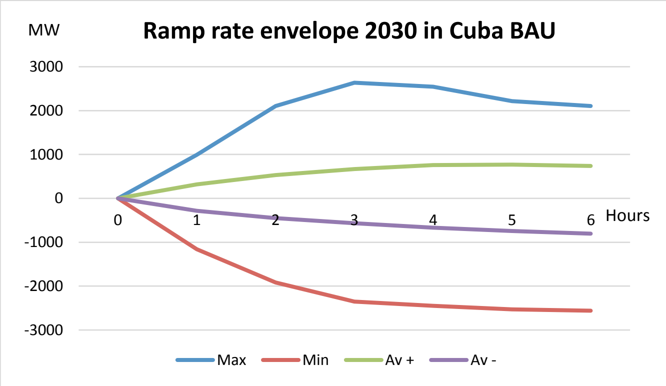

Figure 4. Ramp rate envelope for the Cuban fossil based production in 2030 in the BAU scenario.

The constructed scenarios clearly show that the increased amount of intermittent renewable energy supply will pose serious challenges in the control of the supply-demand balance and electricity transmission. Required ramping capacity originating e.g. from mismatch between daily load curve and solar PV production is considerable. It is obvious, that also demand side response (flexible loads) will be required to balance the system.

3. 100% RENEWABLE ENERGY SUPPLY SCENARIOS FOR CUBA: PRELIMINARY REASONING

Cuba is at the crossroads of the future development of its energy supply. Cuba can choose to fuel its coming growth in energy consumption with conventional fuels, or it can choose to use its abundant renewable energy sources.

The first analysis of possible 100% renewable energy supply scenarios (Hohmeyer and Welle, 2018) has shown that Cuba has a vast solar energy resource (more than 170000 MW) as well as a very substantial good wind energy resource (around 19000 MW). Besides these two major renewable energy sources, Cuba can utilise a large biomass resource from agricultural and forest residues as well as a moderate use of energy crops. What is more, Cuba has sufficient hydropower resources and areas with more than 300 m altitude drop, which can be used for building the necessary pumped hydro storages required for a 100% renewable energy supply system. These five major components (solar PV, wind energy, biomass, hydropower and pumped hydro storages) can supply all the electricity needed for Cuba, even if most other energy uses will be converted to electricity and if the transport sector will be fully converted to e-mobility.

Assuming substantial economic growth from 2017 to 2040 the present electricity demand of app. 20 TWh/a may grow even up to 60 TWh/a in 2040 (different scenarios: 28 TWh/a for the BAU, 44 TWh/a if other non-electric consumption in the residential and industry sectors is converted to electricity, and 60 TWh/a if the entire transportation sector is converted to electricity). The analysis of (Hohmeyer and Welle, 2018) has shown that the combination of 14500 MW wind energy, 8400 MW solar PV, 1500 MW biogas, 236 MW hydropower and 3000 MW pumped hydro storages together with the use of biodiesel in the existing 2500 MW of diesel generators as an ultimate system back up, can supply all of Cuba's electricity demand for a 60 TWh/a scenario including the e-mobility and the substitution of natural gas and mineral oil in the residential and industrial sectors.

What is more, the levelized cost of electricity (LCOE) of such 100% renewable energy system is approximately the same as the present (2017) electricity generation cost based mainly on imported and domestic mineral oil products (see Hohmeyer and Welle, 2018).

Considering the results of this first analysis and the future development of the global climate policy and the high volatility in the global crude oil market, a decision to pursue an energy system transformation towards a 100% renewable energy supply offers a number of significant advantages over a fossil fuel based strategy:

i. It will massively reduce the drain of hard currency for fossil energy imports in the range of 400 to 500 million USD/a
ii. It will substantially increase Cuba's economic growth due to the fact that imports can be substituted by domestic renewable energy sources
iii. It will massively reduce the CO_2 emissions of Cuba by about 50 Million tons per year (as compared to a fossil fuel based power supply)
iv. It will massively reduce local air pollution due to the use of clean green electricity in power production, transportation, households, industry and commercial sector.

v. It will allow the direct access to massive international climate funding to help in the transition to the 100% renewable energy system.

The great advantage that Cuba has as compared to highly industrialized countries is the fact that less than 30% of its future capital stock for power generation is existing today. Thus, Cuba still has the freedom to choose, while the most of the industrialized countries will need to decommission relatively new operating fossil fuel fired power plants because of the necessary introduction of high shares of renewable energy generation.

4. GRID STRUCTURE AND CONTROL ISSUES IN THE FUTURE CUBAN ENERGY SYSTEM

Introduction of the DG concept has emerged different challenges related with system integration, procedures and technical recommendations derived from national and international regulations (Castro et al., 2018). Utilization of DG structure brings improvements in power quality indexes, voltage regulation and power factor correction compared with the centralized generation approach (Blaabjerg et al., 2004). By reducing distance between generation units and electrical loads, power loss in transmission and distribution system will be decreased as well as ancillary services such as reserve systems and reactive power compensation will be provided by DG units (Arboleya et al., 2010).

Already in existing Cuban system, the presence of more than 200-generation nodes has imposed changes in the management of the national energy system (NES). The upper level concept of the grid management has been maintained as centralized, but the operation of individual power plants has been delegated to provincial companies. This regional level forms the lower level of the management scheme of the NES.

According to the governmental plans, the grid connected power generation capacity will be increased 2400 MW or even more by 2030. This will definitely lead to changes in the control scheme of the power system e.g. requiring voltage control by static voltage compensators (SVC) in the connection nodes where the new generating units will be connected. Already in 2017 there were installed a new SVC unit in the central part of the island to improve the transmission efficiency between western and eastern parts of the country.

The Electric Test and Research Centre, CIPEL, has carried out several research projects about the effects of the planned DG structure to the Cuban power system (Castro et al. 2011; Castro et al. 2016 a, b; Santos et al. 2012; Santos et al. 2017; Santos 2017). CIPEL has also analyzed the effects of increased share of RES in the national grid (Vilaragut et al. 2012, Torres et al. 2016, 2017). The results have shown that with internal combustion engine driven power plants applied in Cuban power system, it is important to recognize voltage, current and power oscillations caused by irregular torque of primary movers (engines). Other reasons for system oscillations are e.g. constructive eccentricities, unbalance between phase currents, time and spatial harmonics, and changes in systems configuration.

It is demonstrated that if the injected power to a node stays inside the permitted limits, new RES generation units and DG schemes do not require additional compensators or cause any major problems to the Cuban grid. This holds up even in case of the worst operating conditions, as long as the operating conditions and the power limits stay inside the limits (see Figure 5).

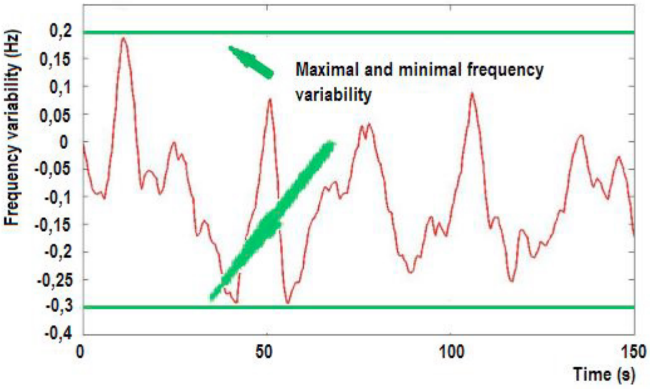

Figure 5. Frequency fluctuation caused by 5 MW PV plant, 2,5 MW Wind power plant and 8 MW electric load in one Cuban region. Source: (Santos et al, 2017)

It is possible to increase the share of intermittent renewable power generation in the Cuban grid with the use of energy storages, such as electric batteries and pumped hydro storages. The effect of using storages to the frequency stability is shown in Figure 6 (Castro et al. 2016 b).

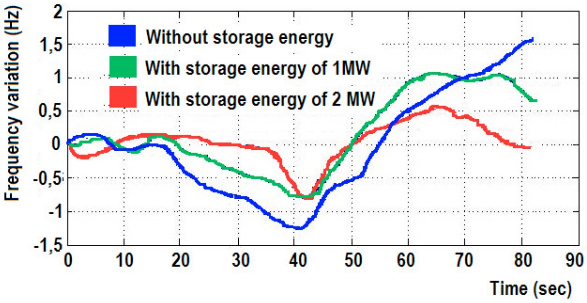

Figure 6. Frequency fluctuation caused by the drop of 3 MW PV generation with and without energy storage. Source: (Castro et al, 2016 b)

Installation of RES Power Plants along the Cuban island will also reflect on the grid configuration. It is necessary to be able to change the grid topology according to the state of the power system by opening the normally closed sectionalizing switches and closing the normally open tie switches (Bouhouras and Labridis, 2012). Changing the network topology affects the power losses striving distribution system operators to find the optimal configuration in such a way that the losses are minimized and the operational constraints are not violated (i.e., voltage and current limits, feeding all loads, and radial structure).

High level integration of RES in the power systems requires also utilization of modern power system components and monitoring systems to improve the efficiency and the security of the grid. E.g. reactive power compensation for maintaining the transfer capacity of the grid, DG node based voltage regulation, low voltage and frequency ride throughs to improve the operation security of the power system under challenging operation conditions.

Increased share of intermittent renewable generation challenges performance requirements of the system controllability. Figure 7 illustrates the typical present daily load profile and load share in the Cuban power system. Base load is supplied by heavy and medium light oil fired steam power plants and controllable power is generated by petrol and diesel fuelled engine power plants and gas turbines.

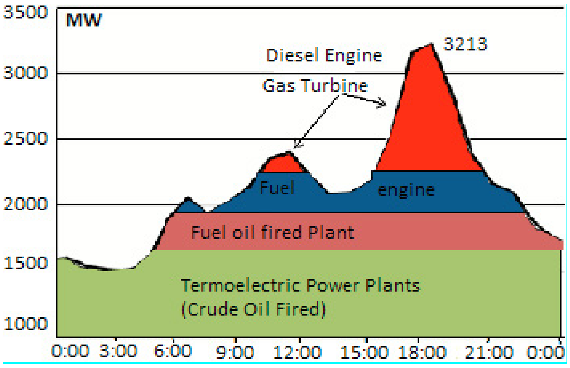

Figure 7. Typical present load curve and load share in Cuban power system. (JICA 2016)

According to future scenarios (Fig. 3) heavy fuel oil fired base load generation will be replaced by biomass fired thermal generation, solar PV, and wind generation. Capacity of controllable gas turbine, diesel and light fuel oil fired generation will remain more or less constant being app 2800 MW. According to calculated ramp rate envelope (Fig. 4), the available controllable capacity should be enough to cover the required average control capacity. But if the calculated minimum and maximum ramp rates will be realized, additional capacity will be needed. Possible ways to get additional controllable resources are demand response, energy storages, and taking also biomass fired thermal CHP generation as a part of the control task force. Controllability of electric power generation of CHP plants can be achieved by installing condensing low pressure turbines (tails) after back pressure turbines, using turbine bypassing pressure reduction valves to adjust heat power ratio of the generation, or installing thermal storages to decouple the heat load demand from boiler operation point for a while. (Korpela et al., 2017)

Replacement of steam turbine driven synchronous generators with converter based asynchronous generation (solar PV and wind) will reduce the inherent power system inertia and deteriorate the frequency stability. If the share of asynchronous generation is growing too high, it might be necessary to exploit also asynchronous generation units to frequency control. This can be done by operating PV-panels and variable speed wind turbines little aside from their maximum power point values, and utilizing this quickly activated power resource for frequency control. (Liu et al., 2013) Also battery storages are very suitable for frequency control.

5. RESULTS AND FINGINGS

Evolution of the power system from the centralized fossil fuel fired generation system to the distributed renewable generation system leads to complex challenges. As a policy decision, Cuba is changing its energy matrix by implementing four types of RES power plants and installing them along the island. This is not only a political issue, but it requires changes in the existing power system structure and new skills from people involved with the system design and operation. However, the great advantage that Cuba has as compared to highly industrialized countries is the fact that less than 30% of its future capital stock for power generation is existing today. So the evolution of the power system can be implemented via natural renewal and expansion of the existing system.

The future power system must be designed based on modelling and simulations of loads and distributed generating units (Atwa et al, 2010). Energy planning tools and national/regional system models based scenarios shall be used to define the boundary conditions for future system design. Modelling and scenario building is a multidisciplinary task. Workshops participated by engineers, economists and officials from relevant government departments are proved to be a good practice for knowledge acquisition and working with models. Scenarios give us answers how much generating capacity will be needed, how the consumption and generation profiles will be changed, and how much and which type of flexibility will be needed to keep the system running. Scenarios will also give the background for the economic analysis of the required investments and future price of energy. One important issue in system planning is weather conditions. Caribbean islands are annually hit by strong hurricanes damaging PV parks and wind farms. This should be recognized in the planning of system structures.

Dynamic analysis of the power system with high share of intermittent renewable generation has a very special role in the system design. Controllability of the power system consists of dynamic characteristics of both consumption and generation sides. To make the system controllable, dynamic performance (ramping speed, controllable capacity, accessible load levels) of the generation side must match with the dynamic characteristics of the consumption side. In future systems, it is no more possible to balance the system by generation control only, but also demand response is needed to shape the dynamics of the consumption side. Energy storages will also have remarkable role in future energy systems. Increased capacity for fast reacting control capacity for frequency control is also required to compensate the reduced inherent inertia of the power system.

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