Planning for electricity generation fully based on renewable energy systems

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***Abstract*—This paper proposes and discusses planning approaches for the development and operation of renewable energy systems for electrification. The approaches presented here are based on consumption pattern analysis. Consumption pattern of Madeira, Portugal is presented as an example. The proposed approaches include scenarios where electricity is fully supplied by renewable energy sources as well as a scenario where the objective is to increase the penetration of renewable energy systems.**

Keywords—energy planning, consumption pattern, peak demand, energy optimization

I. Introduction

Application of renewable energy sources to meet energy demand is likely to increase because of depletion of fossil fuel sources [1] and climate considerations as replacing fossil fuels with renewable energy technologies lowers carbon intensity [2]. There are several methods to plan for the development and expansion of renewable energy systems in electricity sector. Some methodologies for planning these systems are optimization strategies such as cost minimization, maximization of the Project Lifetime Economic Return, minimization of CO_2 emission and minimization of the fuel price risk due to the use of non-renewable energy sources [3]. Likewise, renewable energy systems can also be planned by investigating demand response [4]. For instance, active controller has been proposed [5] for a smart grid with high penetration of renewable resources to analyze consumption pattern and optimize cost and reliability. This paper proposes several approaches to design renewable energy systems for electrification based on analysis of electricity consumption patterns. Consumption pattern of main island of Madeira, Portugal is taken as a reference case. Madeira is an autonomous archipelago of Portugal and the main island considered in this paper does not import electricity from elsewhere. Therefore, the approaches presented in this paper are most applicable for small-scale grid infrastructure including islands and small developing or underdeveloped nations like Nepal. The objective of this paper is to develop computationally inexpensive design strategies for renewable energy development in electricity sector. Hence there is no requirement of high performance computing and processing power.

II. Consumption Pattern Based Analysis

A. Madeira electrification scenario

Madeira Electricity Company, a government owned entity, is responsible for generation, transmission and distribution of electricity in Madeira [6]. In 2015, the total installed capacity of power plants in the main Madeira island was 325.97 MW of which the sizes of thermal, hydro, wind and PV plants were 211.04 MW, 50.67 MW, 45.11 MW and 19.15 MW respectively [7]. The corresponding energy supplied by these plants were 670.37 GWh, 66.49 GWh, 73.64 GWh and 25.01 GWh.

B. Analysis of consumption pattern

Electricity consumption patterns for main island of Madeira are analyzed here for different temporal resolution. Fig. 1 shows power consumption on the main island of Madeira on a 7th of May 2015 with hourly resolution. This date is representative of a random typical weekday. Similarly, Fig. 2 shows power consumption with hourly resolution on 10th of May 2015 which represents a typical weekend. The horizontal straight lines in the figures represent average values. It is observed that a weekday typically has a slightly higher (roughly by 18%) power consumption than a weekend day in Madeira. This could be because of the effect of consumption by service sector which operates only on weekdays. Fig. 3 shows power consumption on 28th of July, 2015 as this day has the highest energy consumption for 2015. The highest daily energy consumption on the day of July can be expected in Madeira as the island hosts several sports and other events during summer and experiences high influx of tourists.

Fig. 4 shows power consumption on 24th of December, 2015. It is seen that this day has a short period where power consumption is the highest for 2015, as opposed to 28th of July, 2015 which has the highest energy consumption of 2015. This shows that the day when energy consumption is highest can be different from the day/instant when power consumption is highest in Madeira. Monthly energy consumption pattern is shown in Fig. 5 where higher energy consumption is seen in summer for reasons explained above. Fig. 6 shows daily average power consumption pattern for the year 2015 with the horizontal straight line representing average value.

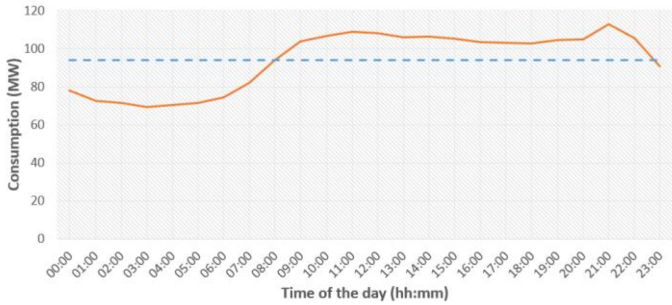

Fig. 1. Hourly power consumption for a typical weekday of 2015

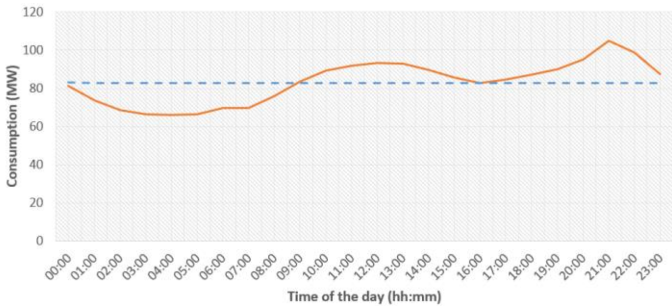

Fig. 2. Hourly power consumption for a typical weekend of 2015

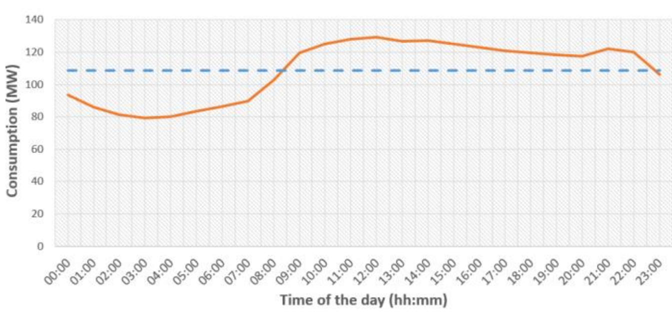

Fig. 3. Hourly power consumption for the day consuming maximum energy in 2015

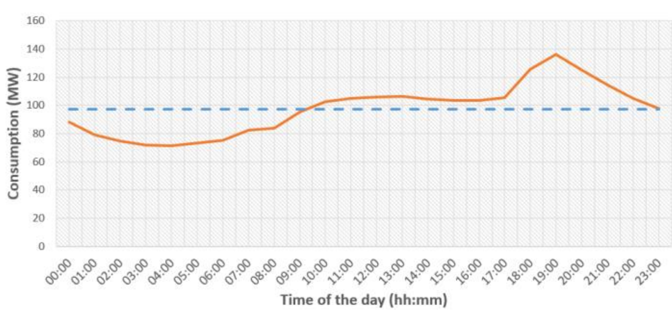

Fig. 4. Hourly power consumption for the day consuming maximum power in 2015

It is found that the energy consumption on 28th of July (represented by area under the curve of Fig. 3) is 2.6 GWh which is the highest for any given day of 2015. On the other hand, maximum power consumption for 2015 is noted at around 19:00 hour on 24th of December as can be seen in Fig. 4. This maximum power consumption is approximately 136 MW.

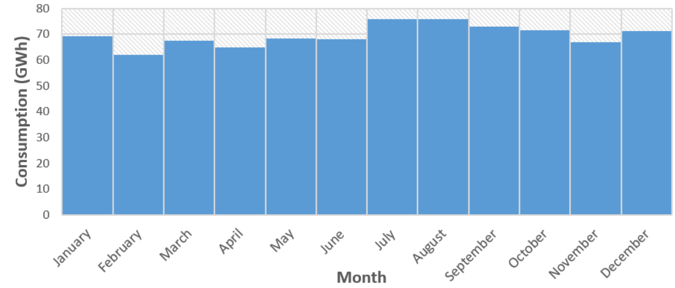

Fig. 5. Monthly energy consumption for 2015.

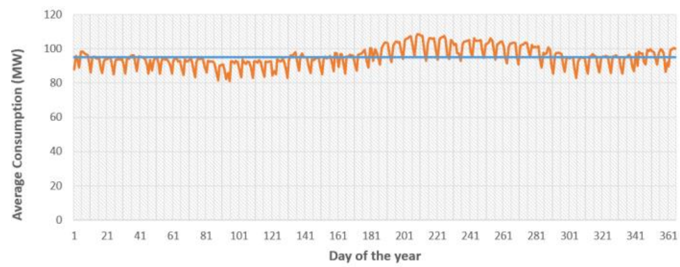

Fig. 6. Daily average power consumption for the year 2015

III. ELECTRICITY GENERATION PLANNING

There are several approaches to energy planning [8, 9] that considers different factors such as cost, risk and environment among other parameters. In this section, three approaches to electricity generation planning are presented that consider cost or environment or increased penetration of renewable energy in the grid. Scenarios that include fully renewable energy systems as well as a scenario that reduces power generation by fossil fuel sources are considered. For scenarios where electrification is fully done by renewable energy sources, the technologies considered are solar PV, hydropower and wind energy systems. All approaches presented here are based on analysis of electricity consumption pattern.

A. *Cost optimization approach*

This approach calculates generation cost per kWh of energy for different scenarios and then selects the scenario with least cost. First, installed size and technology to meet the base load is designed which operates 24 hours a day at nearly 100% of its capacity. Then, intermediate power plant is designed to meet the intermediate load, which is calculated as average power plus two standard deviations in this paper, and finally power plant to meet the peak load is designed.

In the case of Madeira, the minimum power consumption for 2015 was found to be 62.37 MW. Therefore, single or multiple power plants of a total size of 65 MW can be selected to supply base load. In this way, the power plant(s) would run at least 96% of its rated capacity at any given moment of time maintaining the near maximum efficiency. Resource availability largely governs the selection of base load renewable energy plant as a technology cannot be utilized as base power plant if it cannot supply the minimum required power continuously throughout the year. For the case of

Madeira, if all three considered renewable energy technologies, i.e., solar PV, hydropower and wind, are assumed to have sufficient resource potential to dispatch base load, technology with lowest Levelized Cost Of Energy (LCOE) is selected in this approach. The LCOE is defined as [10]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where, I_t is investment expenditures in the year t, M_t is operation and maintenance expenditures in the year t, F_t is fuel expenditures in the year t, E_t is electricity generation in the year t, r is discount rate and n is life of the system.

Since the installed sizes of hydropower, wind and solar PV are 50.67 MW, 45.11 MW and 19.15 MW respectively in Madeira, the additional sizes of the corresponding technology to meet base loads are approximately 15 MW, 20 MW and 46 MW respectively. Therefore, the LCOE for 15 MW hydropower, 20 MW wind power and 46 MW solar PV are calculated and the technology that gives the lowest LCOE is selected.

The yearly average and standard deviation of power consumption for Madeira are approximately 95 MW and 6 MW respectively. The intermediate power plants size is designed to meet the requirement of average power plus two standard deviations i.e. 107 MW. Thus, if the power consumption is normally distributed, the demand of above 95% is met. Since the size of plant providing base load is 65 MW, the size of intermediate power plant for Madeira is 42 MW. The intermediate power plant is also designed by considering several renewable energy candidates and selecting the one with lowest LCOE. Finally, the peak power plant is designed, which is also selected based on the lowest LCOE. The size of peak power plant is the remaining power demand after meeting the intermediate power demand. In the case of Madeira, the peak power demand was on 24^{th} of December due to Christmas and this peak power was approximately 136 MW for the year 2015. Therefore, the size of the peak power plant is 29 MW.

B. Envvironmental consideration approach

This approach considers equivalent CO_2 emission of renewable energy technologies to design power plants. The technology that generates lowest equivalent CO_2 emission per kWh is given priority for development. There are life cycle assessment and other studies [11, 12] that indicate that wind energy have relatively low whereas solar PV have relatively high CO_2 emissions per kWh. This could indicate that the choice of technologies for Madeira should be in the following order: wind energy, followed by hydropower and finally solar PV, according to this approach. However, the exact emission can be site dependent and cannot be generalized.

In addition to equivalent CO_2 emission, there can also be local environmental impacts of renewable energy technologies. These local impacts also have to be considered. A quantification strategy to measure environmental impacts can be developed to make this approach robust. As land requirement and water consumption [11] are examples of important indicators to assess local environmental impacts of renewable energy technology, these indicators can be considered wherever applicable. For example, land requirement of solar PV has been found to be a challenge in California [13]. Similarly, noise pollution and killing of birds have been linked with wind energy [14]. Likewise, harmful impacts on fishes and loss of local biodiversity have been linked with hydropower plants [15].

C. Renewable energy share increment approach

The previous two approaches discussed above are for scenarios where only renewable energy sources are used. However, in many cases, there are scenarios where regional governments are trying to increase the share of renewable energy in their existing infrastructure that is mainly based on fossil fuel. This approach is for such case and can be used to plan for increment in the share of renewable energy. The proposition of this approach is to gradually reduce the use of fossil fuel power plants and eventually use these plants only for base load supply. This proposition is based on a fact that traditional fossil fuels are dispatchable energy source and therefore make suitable candidates for continuous power supply. In order to reduce the reliability risk, gradual replacement of individual fossil fuel plants starting from the smallest plant is proposed such that the plants are replaced in the ascending order of their sizes by renewable energy plants. For instance, the total installed capacity of 211.04 MW of thermal plants in Madeira is because of three plants of capacities 167.04 MW, 36 MW and 8 MW. Therefore, the proposition is to first replace 8 MW plant followed by 36 MW plant, and finally 167.04 MW. Replacement of the smallest fossil fuel plant per replacement period allows the power supplier company to study the characteristics of the renewable energy plant installed to replace the fossil fuel plant thereby minimizing the risk. It is noteworthy that the size of renewable energy plant required to replace 8 MW of thermal plant can be higher than 8 MW because renewable energy sources are generally non-dispatchable. Therefore, the energy (in terms of MWh) supplied by the thermal plants have to be matched with the energy supplied by the renewable energy plants that shall replace the thermal plants. It is also worthwhile to mention that thermal plants generally operate in several clusters with each cluster containing several units of generators. For instance, the 167.04 MW thermal plant in Madeira has 4 clusters and a total of 16 generators [7]. Therefore, the 167.04 MW thermal plant can be phased out by replacing one cluster at a time by renewable energy system.

The selection of renewable energy plants to replace 8 MW, 36 MW and eventually 167.04 MW of thermal plants can be based on the cost or environmental approaches discussed in previous subsections. Apart from resource availability, which is always a governing factor while selecting renewable energy technology, a factor to consider can be energy mix to enhance energy security [16].

IV. CONCLUSIONS

Three approaches to plan for the development and integration of renewable energy systems in electricity grid are proposed by taking into account the electricity consumption pattern. These approaches are illustrated by taking the case of Madeira, Portugal as an example. However, it is noteworthy that these approaches are applicable for all types of small to medium electricity grid and are not limited to Madeira. The approaches presented here can be used to design electricity generation systems that are fully renewable energy based. Additionally, the third approach can be used to increase the penetration of renewable energy on the grid that contains fossil fuel based thermal plants.

Extension of these approaches can be carried out in further studies. For instance, optimization algorithms can be developed to find out least cost of electricity generation. Furthermore, metrics to quantify environmental impacts can be developed.

V. ACKNOWLEDGMENT

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