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Battery Size Impact in Green Coverage of Datacenters Powered by Renewable Energy: A Latitude Comparison.

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Abstract The use of renewable energy is a major trend to meet datacenters energy needs. However, its intermittent nature requires energy storage devices to store the over produced energy when not being used. Thus, the green coverage value, representing the fraction of total energy consumption covered by renewable energy, is increased. In this paper, we analyze the impact of using different battery sizes to optimize renewable energy usage. We have built a battery simulation tool able to provide the battery state, track the amount of stored and used energy by the battery as a function of the energy consumed by a datacenter and the energy produced by solar panels. We show the impact of battery size on the green coverage percentage, green energy loss, and brown energy taken from the traditional grid. A comparison of these metrics is made for three different geographical locations at 10 °, 35 °, and 60 ° latitude. We discuss the competitiveness of constructing datacenters in different geographical locations based on the results.

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1 Introduction

Following an invariant growth in the required computational capacity, the total energy combustion of datacenters increases over time. In 2010 the energy consumption of data center was already estimated to represent between 1.1% to 1.5 % of the worldwide electrical energy production [1]. A recent study [2] predicts the energy consumption of datacenters in US alone will reach 73 TWh in 2020, representing more than 5 times the production capacity of one new EPR nuclear reactor.

In order to decrease the CO_2 footprint of datacenters, the use of renewable energy is required. Nevertheless, the production of energy from renewable resources, such as sunlight and wind, is variable over time and dependent of weather conditions. One common way to address this problem is to use batteries, not only as a backup in case of energy outage or as a power peak shaving, but as an energy storage device. More and more studies [3], [4], [5], [6] propose the usage of batteries as a key source of energy for the energy system supply of a datacenter. In this case, the main question to be tackled is: how to choose the battery capacity to maximize the renewable energy usage thus minimize the green energy loss. The concept of green coverage mentioned in this paper represents the percentage of total energy consumption provided by renewable energy. Furthermore, we investigate how different geographical locations affect the required battery size to reach a desirable green coverage.

In November 2017, Tesla finished the construction of the worlds largest energy storage installation with a capacity of 129 MWh [7]. This demonstrates the technology readiness of current large battery farms.

Figure 1 illustrates the energy sources system for our study.

We consider a datacenter consuming energy, which is provided by one of these three sources: renewable energy, battery energy and grid energy, according to this order of priority. The battery gets charged only by the renewable source and it charges only when the renewable energy is of greater amount than the datacenter energy needs. If the battery is full and there is still renewable energy produced and therefore not being used, this extra energy is considered overproduction. The battery discharges when datacenter energy consumption is higher than what is provided by renewable sources. In cases when both, renewable sources and the battery, are not enough to fulfill the datacenter energy requirements, additional energy is taken from the traditional grid (also referred to as brown energy).

The remainder of this paper is organized as follows. Section 2 presents recent work on battery usage as an energy source for datacenters. Section 3 describes solar energy analysis for three selected countries. Section 4 introduces a simulator tool we built to model and predict battery energy over time based on a battery as a finite state machine perspective. Section 5 describes the experimental setup and scenarios, as well as the results with the interpretations. Lastly, Section 6 concludes this paper and discusses future work we plan to advance and generalize our study.

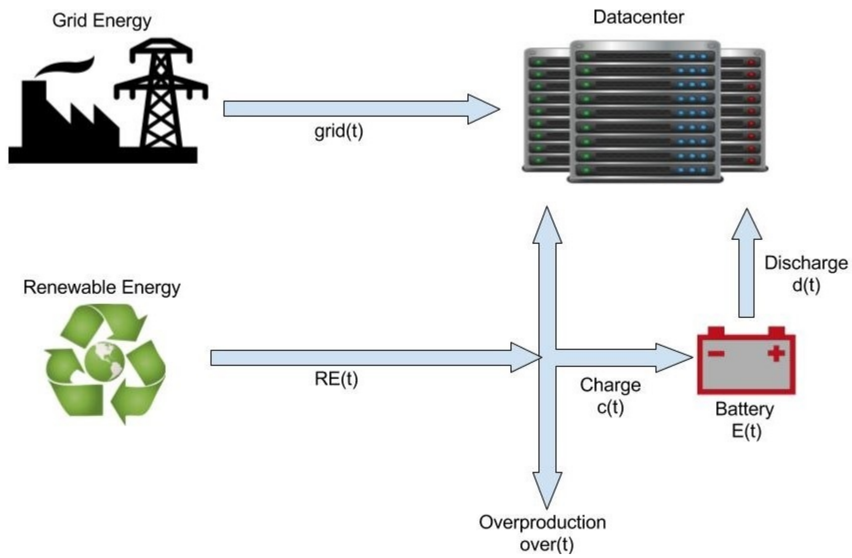

Fig. 1 Illustration of energy sources balance in our study.

2 Related Work

Energy storage devices (ESD) have largely been involved as a means of backup against power outages or to shave power peaks. However, several recent review papers focus on latest usages of batteries as a key supporting source of energy combined with renewable energy sources. The authors in [3] theoretically describe important characteristics of different ESD technologies, the trade-offs of placing them at different levels of the power hierarchy, and quantify trade-offs as a function of workload properties. [4] presents an overview of energy storage in renewable energy systems, describing advantages and drawbacks of different storage technologies. [5] categorizes existing research works according to their basic approaches used, like workload scheduling, virtual machine management, etc. Meanwhile [6] describes energy storage systems with detailed classification, features, advantages, environmental impacts, and implementation possibilities. The large number of references shows high interest on the topic of using batteries for several purposes. In our study instead, we present an approach to find the battery size impact on the green coverage for a datacenter and compare this impact for countries in typical northern, medium, and lower latitudes.

Innovative ways to use or study batteries are introduced at articles [8], [9], [10], [11], [12], [13]. Authors at [8] consider two fundamental approaches for improving the usage of renewable energy in a small/medium-sized data center: opportunistic scheduling and usage of ESDs, which store renewable energy surplus at first and then provide energy to the datacenter when renewable energy becomes unavailable.

[9] and [12] propose an efficient, online control algorithm for Datacenter Power Supply System called SmartDPSS and later MultiGreen. MultiGreen allows Cloud Service Providers to make online decisions on purchasing grid energy at two time scales, aiming to leverage renewable energy, and opportunistically charge and discharge batteries, in accordance with the available green energy and lower electricity prices. Authors at [10] study curtailment using the metric of energy return on investment (EROI), defined as the ratio of useful energy extracted from each unit of energy invested. They study the EROI for renewable energy farms when used with several types of storage technologies. [11] presents GreenPlanning, a framework to hit balance among multiple energy sources, grid power and energy storage devices for a datacenter. Results demonstrate that GreenPlanning can reduce the lifetime total cost and emission by more than 50% compared to traditional configurations, while still satisfying service availability requirement. The authors at [13] investigate cost reduction opportunities that arise with the use of ESDs. They consider the problem of opportunistically using these devices to reduce the time average electric utility bill in a datacenter by developing an online control algorithm.The innovation we bring in our paper is a simulation tool for battery energy modeling and prediction, and investigation of the battery size impact in green coverage percentage for different locations.

The issue of energy storage as a future trend for datacenter energy sourcing has been covered also in web articles, magazines, news, etc. The Wall Street Journal [14] claims that the giant battery is whats been missing in the renewable-energy revolution. In Times 2017 article [15], Logan Goldie-Scot, an energy-storage analyst at Bloomberg New Energy Finance cites Energy storage is being viewed by network operators as a potential tool in their toolbox, and that hasnt been the case up until now. While these articles express information on trends and opinions, we perform an experimental study aiming to help datacenter operators make wise decisions on choosing the battery capacity.

3 Solar Energy Analysis

In this section we describe the total amount of renewable energy provided over a year by each of the three selected countries: Finland, Crete, and Nigeria. In our study, only solar energy is considered as a type of renewable energy as it is dependent to geographical location e.g latitude. Wind and other types of renewable energy are more irregular and have less possibility to be modeled based on latitude. Figure 2 graphically represents the total amount of solar energy produced monthly over a year by a 1 m^2 solar panel in Finland, Crete, and Nigeria. Nigeria shows an almost constant solar energy production. Since all days throughout the year last approximately 12 hours, there is only a slight difference between winter and summer months. In Crete, solar intensity provides a large but varying energy production. The winter months provide less sunlight than the summer months, and have therefore a lower energy production than Nigeria. However, due to longer summer days, daily produced solar energy exceeds the energy productions of Nigeria despite of Nigeria's greater solar intensity.

The most varying results are measured in the Finnish location. The winter months produce almost no solar energy because of a very short time of sunlight during the day. On the other hand, during the summer the solar energy production can exceed both Greece and Nigeria because of the long duration of sunlight during the day. These data are also presented in Figure 3 showing respectively highest energy value produced in 1 hour and total amount produced over the whole year for Finland, Crete and Nigeria. We calculate the quantity of solar panels needed to achieve an arbitrary value of 50% green coverage over one year. We base our solar energy production data and assume a total energy consumption of 260 MWh for our datacenter as presented in [17]. Table 1 presents numerically the total amount of annual solar energy provided by a 1 m2 solar panel and the required quantity of solar panels in m2 for the three countries, aiming for half of the datacenter energy consumption to be provided by the solar energy source. On closer observance of the data, we notice a fair similarity between Nigeria and Crete, with only a 17% difference. Almost twice (45%) of the number of solar panels needed in Nigeria are needed in Finland to achieve same target of solar energy production.

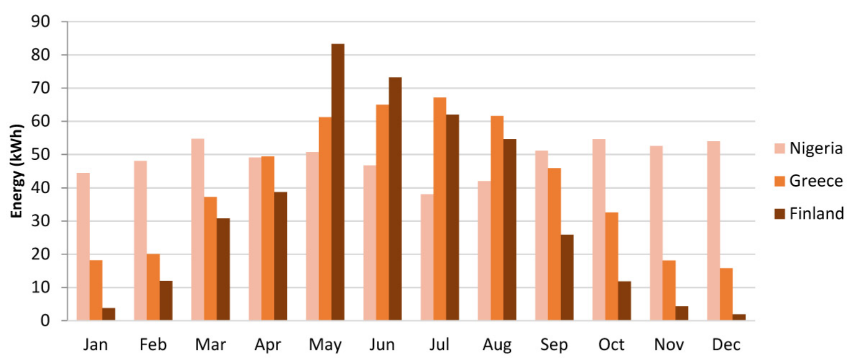

Fig. 2 Solar energy produced by 1 m^2 solar panel in three geographical locations monthly over a year [17]

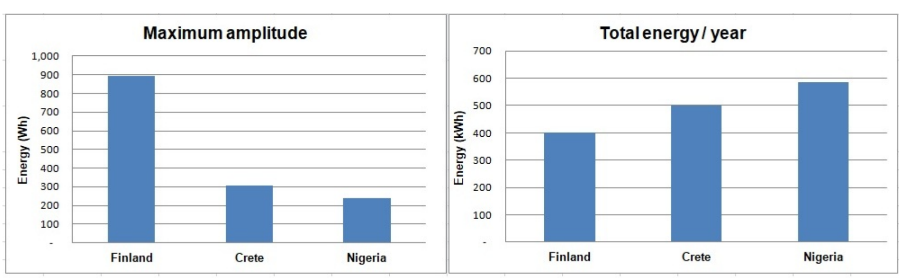

Fig. 3 Maximum amplitude in Wh per country during a year (left) and the total annual amount of solar energy produced per country (right).

Table 1 The total amount of annual solar energy provided by 1 m^2 solar panel and the number of solar panels in m^2 needed to cover 50% of energy consumption for Finland, Crete and Nigeria.

Country	Annual Solar Energy/1m^2 (kWh)	Required solar panels (m^2)
Finland	402	324
Crete	500	260
Nigeria	585	222

4 Battery simulator tool

In order to analyze and being able to predict the amount of available energy in the battery over specific moments in a chosen time period, we developed a simulation tool. The simulator is based on the concept of the battery as a finite state machine, whose trigger conditions are related to the available amount of solar energy and datacenter energy consumption at a specific time *t*.

4.1 Battery as a finite state machine

There are four possible states that the battery can be at any time *t*: Full, Discharging, Charging or Empty. Therefore, there are 16 possible state transition combinations. Practically, all of these combinations are feasible except for the Full - Empty and Empty - Full transitions which are generally limited by the charge/discharge rate of the battery during a certain period of time. Possible triggers from one state to the other depend on the amount of available solar energy in a moment of time *t*, referred to as *RE(t)* (Renewable Energy) and the datacenter energy needs in that moment *t*, referred to as a *consum(t)*. Other affecting factors are the value of the stored energy in the battery, *E(t)* and the maximum energy capacity of the battery named *Efull*.

4.2 Implementation

The pseudocode for developing the simulator is given below as a set of 8 steps. *BS(0)* refers to the initial Battery State assigned to Full, assuming the battery is fully charged when the simulation begins running. Each of the 16 'current - next' state combinations is assigned a combination number (named *combinationNr*), which calculates the energy (*E(t)*) the battery will have on every *t*. The green coverage is calculated according to Equation 2 and printed out. The loop repeats 8760 times for every hour of the year, resulting in outputs of total charging and discharging amount of the battery, overproduction, and grid energy for every hour.

The equation (1) is checked by the simulator to be true for every moment of time *t* during the simulation time period.

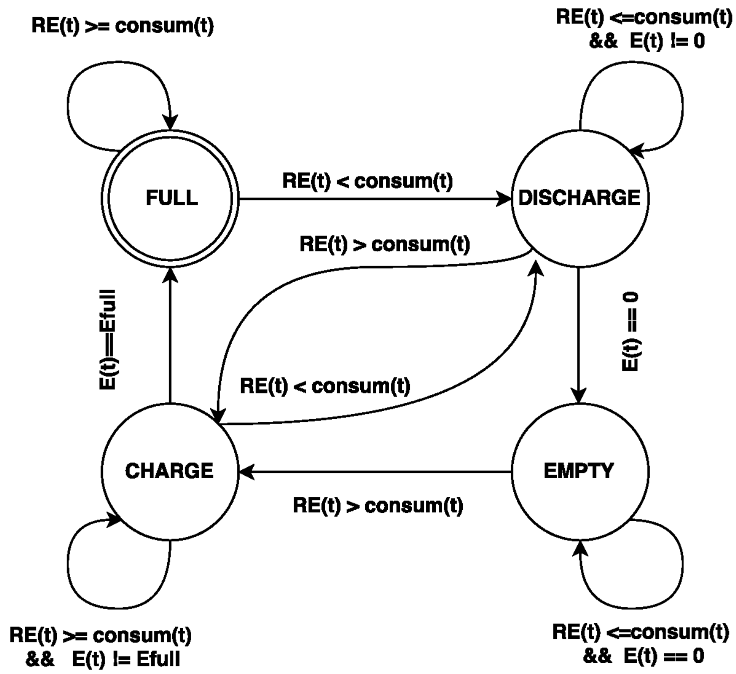

Fig. 4 Battery states over time represented as a finite state machine.

Algorithm 1 Simulator tasks

$BS(0) \leftarrow FULL$, $t \leftarrow 1$
repeat
  Define $BS(t) = f[BS(t-1), RE(t), consum(t)]$
  Define $combinationNr = f[BS(t-1), BS(t)]$
  Calculate $E(t) = f[E(t-1), combinationNr]$
until $t \leq 8760$
$greenCoverage$ = annual $[RE(t) - over(t)]$/annual $[consum(t)]$
Print $charge(t), discharge(t), overproduction(t), grid(t), greenCoverage$

$$RE(t) + d(t) + grid(t) = consum(t) + c(t) + over(t) \tag{1}$$

On the left side of Equation (1) are listed the providing energy sources and on the right side is listed drawn energy. $RE(t)$ represents the renewable energy being produced at moment t, $d(t)$ is the amount of energy discharged from the battery in the time period $(t-1)$ to t, and $grid(t)$ represents the amount of energy taken from the traditional grid at that moment t, in case it is needed to fulfill the datacenter energy needs. The variable $consum(t)$ refers to the datacenter energy consumption at moment t, $c(t)$ is the amount of energy charged to the battery in the time period $(t-1)$ to t and $over(t)$ represents the part of the produced renewable energy which is not consumed neither by the datacenter nor from used to charge the battery. Based on

Equation 1 we calculate the green coverage metric of our specified datacenter over a year, as described in Equation 2. The sum is composed of 8760 hourly values for each of the metrics: $RE(t)$, $over(t)$ and $consum(t)$. We can distinguish two different scenarios from this equation. First, theoretically we evaluate the green coverage simply as total renewable energy over the year divided by total energy consumption over the year. We have no information regarding the overproduction without running the simulations, so we assume it is zero. Second, experimental simulations show that the overproduction is greater than zero, meaning that the real green coverage is less than the theoretical calculated value. The battery size is the key element affecting the minimization of the overproduction value.

$$greenCoverage = \sum_{t=1}^{8760} [RE(t) - over(t)] / \sum_{t=1}^{8760} consum(t) \quad (2)$$

5 Experiments and Results

To perform the experiments we have run the simulation tool by changing the input of battery size from 0 to 10MWh, separately for each of the countries. The first run under battery size equal to 0 shows how much from the produced solar energy is spent in vain as overproduction. Increasing the size of the battery means increased amount of stored solar energy. The yield of this is diminishment of the amount of overproduction and energy taken from the grid, translating to an overall higher renewable energy usage. The optimization concept based on the battery size is related to the fact that as battery size increases, the amount of energy taken from the grid and the overproduced energy is decreased. The decreasing rate depends on the battery capacity and of the energy production pattern, which differs in the selected geographical locations. The simulation time covers a period of 1 year (8760 hours), taking as input the hourly solar energy records and the hourly energy consumption values over the year. The datacenter is composed of 100 servers and we assume in this paper a synthetic variable workload over one week repeated over the whole year. The annual energy consumption for this datacenter equals to 260 MWh. The used synthetic variable workload is obtained as presented in [17].

5.1 Experimental Scenarios

Experimental scenarios represent the number of simulations we have performed and the goal of running each of them. Our simulator tool asks for input the number of solar panels required to achieve a theoretical value of green coverage and the battery size supporting this energy system. For each of the 3 selected countries we have run the simulations requiring the number of m2 solar panels according to Table 1 (222, 260 and 324). Also, the battery size is first chosen to be 0 and then increased to 1 kWh, 10 kWh, 100 kWh, 1 MWh and 10 MWh. We stopped increasing the battery size at 10 MWh as the calculated overproduction value over a year reaches zero and the theoretical annual green coverage equals the annual green coverage calculated from the simulator. After achieving this goal, increasing the battery size furthermore has no practical meaning and brings no change to the metrics we are studying.

5.2 Results and Interpretations

In this subsection we present the results and interpretations of our experiments through Figures 5, 6 and 7. Through empirical simulations we found that to achieve no solar overproduction over a year, a 230 kWh battery capacity is needed for the datacenter located in Nigeria, a 292 kWh battery capacity for the Greece location, and a 9.3 MWh battery capacity if location is Finland. According to a typical Tesla Powerwall 2 battery chosen as a template with a capacity of 13.5 kWh [16], the overall battery size needed is equal to 17, 21, and 688 of such batteries for Nigeria, Crete, and Finland respectively. According to Equation 2, the real green coverage is decreased from the theoretical one in proportion to the overproduction amount. For a theoretical green coverage for the 3 countries, we chose to assign the same value of 50%. The first simulation with battery size 0 for each of the countries shows lower values of green coverage because of the overproduction energy, illustrated in Figure 5. The achieved values are 42%, 35%, and 31%, for Nigeria, Crete, and Finland respectively. This means that out of a desired annual renewable energy usage of 50%, there is an 8%, 15%, and 19% drop from this desired usage because of the total overproduction energy over the whole year. The way to recover from this problem is increasing battery size. Figure 5 graphically shows higher values of green coverage rising towards 0.5 (50%) with increasing battery size. The rate by which this increase happens changes by country, referring to the annual values.

We can notice that Nigeria and Crete achieve 50% green coverage for much smaller battery size. Note also that the battery scale for the x-axis is not linear but rather intentionally distinguishes the values of 230 kWh, 292 kWh, and 9300 kWh to show the battery size needed for the overproduction to be equal to 0.

An increased value of green coverage is the result of a diminished amount of overproduction energy. Figure 6 shows the decreasing rate of overproduction by increasing the battery size for three countries. This happens because the battery stores more of the surplus solar energy, so there is less unused amount of it. Overproduction goes towards zero and reaches it when battery size is 230 kWh for Nigeria, 292 kWh for Crete, and 9300 kWh for Finland. We can notice that Finland is clearly distinguishable for very slow rate of impact by the battery size. This mainly happens because of its solar energy characteristics over the whole year, with high contrasts between winter and summer.

Higher green coverage leads to less amount of brown energy taken from the grid. This concept is shown in Figure 7. Out of 260 MWh, only half of it (130 MWh) should theoretically be taken from the grid for a green coverage of 50%. The ex-

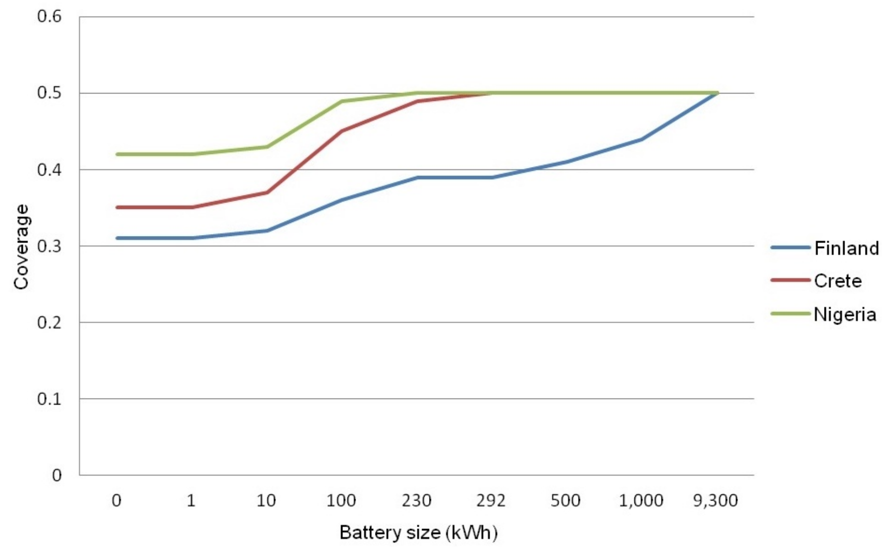

Fig. 5 The value of achieved average green coverage over a year with increasing battery size for Finland, Crete, and Nigeria, under the conditions of Table 1.

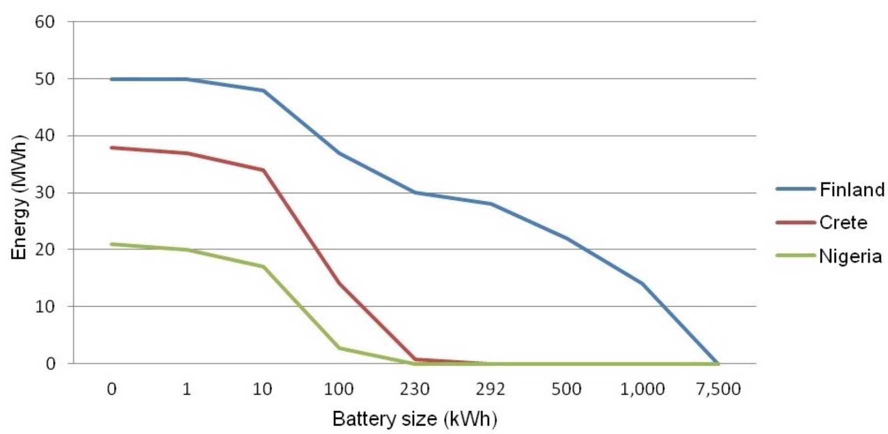

Fig. 6 The amount of overproduction in MWh for one year achieved by increasing battery size for Finland, Crete, and Nigeria, under the conditions of Table 1.

periments show that for battery size equal to zero, the real amount of brown energy would be 150 MWh, 167 MWh, and 179 MWh for Nigeria, Crete, and Finland. This amount reaches 130 MWh by increasing the battery size up to the key values of 230, 292, and 9300 kWh for each of the countries.

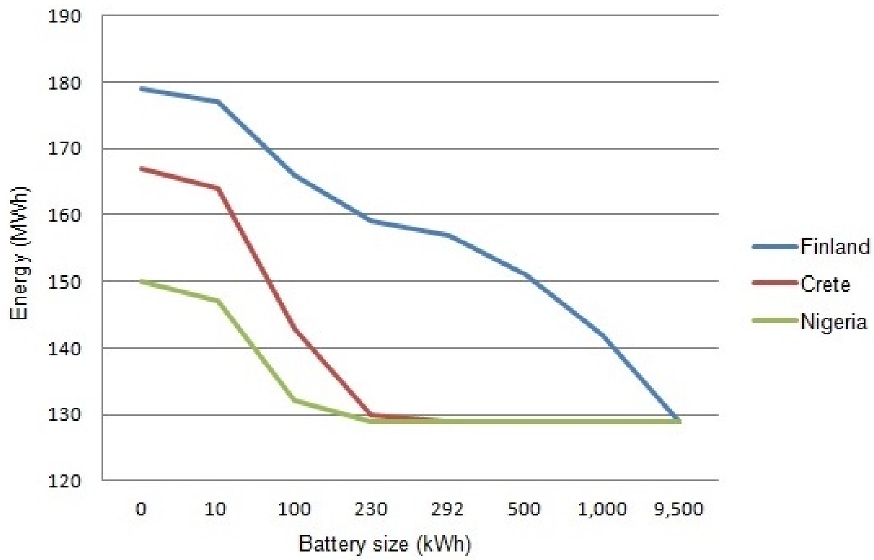

Fig. 7 The amount of energy in kWh taken from the traditional grid for a year with increasing battery size for Finland, Crete, and Nigeria, under the conditions of Table 1.

6 Conclusions and Future Work

The renewable energy sources are a promising means of energy supply for current datacenters. Nevertheless, they can be in excess or less than needed because of their variability, bringing the need of batteries as energy storage devices. In this paper, we investigate the impact of battery size in green coverage and green energy loss. We also study how different geographical locations affect the required battery size to reach a desirable green coverage.

We built a battery simulator to provide the amount of available battery energy every time t in a chosen time period. We chose a 260MWh/year datacenter, 50% green coverage, and ran the simulator for three selected countries: Finland, Crete, and Nigeria. The results show that the solar panels needed in Crete and Finland are slightly more than Nigeria, 17% and 45% respectively. However, though Finland provides only 15% less annual amount of solar energy compared to Nigeria, it requires a battery size of 39 times greater to achieve wasted energy at level 0. While in Crete, battery capacity of only 27% greater than Nigeria is needed for this goal.

We plan to generalize the given solution for a required percentage of green coverage and a specific geographical location taken as an input from the user. We also intend to apply genetic algorithms for finding the best match of solar panels quantity and battery size in order to keep grid and overproduced energy at minimum possible values.

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